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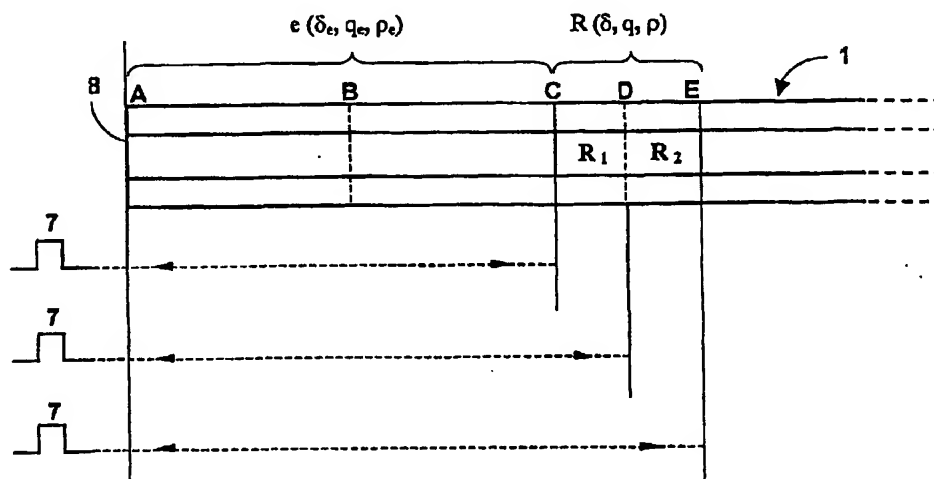
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(54) Title: OPTICAL FIBRE BACKSCATTER POLARIMETRY



(57) Abstract: A method of and apparatus for determining the spatial distribution of polarisation properties of an optical fibre (1). Pulses (7) of light are transmitted along the optical fibre (1) and the polarisation state of light backscattered from portions *e* and elements *R* of the optical fibre (1) detected. A spatial distribution of linear retardance δ , orientation of linear retardance axes *q* and circular retardance axes can be accurately determined. This has application in the analysis of Polarisation Mode Dispersion (PMD) in telecommunications as well as, *inter alia*, strain, stress, temperature and electric current and voltage measurement using optical fibres.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

OPTICAL FIBRE BACKSCATTER POLARIMETRY

The present invention relates to optical fibre polarimetry and, in particular, to a method and apparatus for determining a spatial distribution of the polarisation properties of waveguide or optical fibre.

Knowledge of the polarisation properties of waveguides has various uses. For example, certain polarisation properties of waveguides such as optical fibres of telecommunications systems, used to transmit signals, can lead to degradation of the transmitted signals. Such signals tend to comprise very short pulses of light. As the light pulses travel along an optical fibre, the polarisation state of the light pulses is altered by the polarisation properties of the optical fibre. This alteration of polarisation tends to result in the light pulses becoming less distinct from one another and, over large distances, e.g. tens of kilometers, for high transmission rate, e.g. 40 Gbit/sec, systems, the light pulses can become indistinguishable. This problem is known as Polarisation Mode Dispersion (PMD) and is currently considered to be a major factor limiting the rate at which signals can be transmitted through optical fibre as well as the length of optical fibres over which signals can be sent. Measurement of the polarisation properties of optical fibres is therefore useful in identifying optical fibres or parts of optical fibres in transmission systems that have high PMD so that they can be replaced or by-passed for example. Likewise, measurement of the polarisation properties of optical

fibres during or after manufacture can improve manufacturing processes or quality control for example.

Other reasons that it is useful to determine the polarisation properties of optical waveguides arise due to the polarisation properties of optical fibre being influenced by external factors. For example the polarisation properties of an optical fibre may change when the optical waveguide passes through an electric or magnetic field. Knowledge of the polarisation properties or changes in polarisation properties of the optical fibre can therefore enable measurement of the external electric or magnetic field and consequently electric current or voltage. Similarly, polarisation properties of an optical fibre are influenced by physical forces applied to the optical fibre. For example, stress or strain such as twisting or bending the optical fibre changes the polarisation properties of the optical fibre and knowledge of the polarisation properties of the optical fibre can therefore provide measurement of the stress or strain. Indeed, it is even possible to measure temperature according to changes in the polarisation properties of an optical fibre, as the optical fibre can be arranged to experience strain under thermal expansion and contraction for example.

In "Polarisation Optical Time Domain Reflectometry", Rogers A.J., Electronics Letters, 19 June 1980, Vol. 16, No. 13, pp 489-490, a technique for analysing the polarisation properties of optical fibres is discussed. This technique is known as Polarisation Optical Time Domain Reflectometry (POTDR).

POTDR involves transmitting a pulse of polarised light along an optical fibre. As the light pulse travels along the optical fibre, some of the light is scattered by small imperfections and inhomogeneities in the optical fibre. Such scattering mostly occurs according to Rayleigh's Law, i.e. due to imperfections and inhomogeneities that are smaller than the wavelength of the light propagating along the optical fibre and the scattering does not, in itself, generally change the polarisation of the light. Thus, light which is scattered back along the optical fibre to the end of the optical fibre into which the light pulse was transmitted (backscattered light) has a polarisation state that can be used to deduce information regarding the polarisation properties of the optical fibre.

The polarisation properties of an optical fibre can be described completely by three quantities: linear retardance δ ; orientation of the linear retardance axes q ; and circular retardance p . Linear retardance δ and orientation of the linear retardance axes δ are independent of the direction in which light travels along the optical fibre, whilst circular retardance p for light travelling in opposite directions along the optical fibre is equal and opposite. In conventional POTDR, this means that the circular retardance p is cancelled in backscattered light and only linear retardance δ and orientation of the linear retardance axes q are determined from the polarisation state of the backscattered light. POTDR only therefore provides partial information regarding the polarisation properties of an optical fibre. Whilst this has certain applications, the usefulness of POTDR is therefore limited.

In "Computational Polarisation – Optical Time Domain Reflectometry for Measurement of the Spatial Distribution of PMD in Optical Fibres", Rogers A.J., Zhou, Y.R., Handreck, U.A., Proc OFMC'97, September 1997, pp 126-129, an improvement to POTDR is discussed. This improved
5 technique is known as Computational Polarisation Optical Time Domain Reflectometry (CPOTDR).

CPOTDR involves effectively dividing the optical fibre into a series of adjacent elements starting from an end of the fibre into which light pulses are transmitted. Each element is considered to have polarisation properties that
10 are homogeneous, i.e. constant throughout the element, and is effectively further divided into two sections. The polarisation states of light backscattered in each section of each element is determined separately and, from these polarisation states it is possible to determine the full polarisation properties, i.e. linear retardance δ , orientation of the linear retardance axes q
15 and circular retardance ρ , for each element of the optical fibre in turn.

However, the determination of the polarisation properties of each element of an optical fibre by CPOTDR depends on the determined polarisation properties of the preceding element, which in turn depend on the determined polarisation properties of the next preceding element and so on.
20 CPOTDR therefore suffers from accumulation errors. In other words, the error in the determined polarisation properties of an element affects the determination of the polarisation properties of the next element along the optical fibre and so on. This limits the accuracy of CPOTDR and imposes a

limit on the length of optical fibre for which polarisation properties can be determined. A limitation also arises in that the polarisation properties of the optical fibre must be determined starting with an element at the end of the optical fibre from which the light pulses are transmitted into the fibre and then
5 for elements in turn along the optical fibre. It is not possible to start determining the polarisation properties of an element of an optical fibre part way along the optical fibre until the polarisation properties of all preceding elements are known.

The present invention seeks to overcome these problems and,
10 according to an aspect of the present invention, there is provided a method of determining a spatial distribution of polarisation properties of an optical waveguide, the method comprising:

- (a) transmitting pulses of polarised light along the optical waveguide from an end of the optical waveguide;
- 15 (b) detecting a first polarisation state of light emerging from the end of the optical waveguide due to backscattering between the end of the optical waveguide and an element of the optical waveguide;
- (c) detecting a second polarisation state of light emerging from the end of the optical waveguide due to backscattering in a first section of the element
20 of the optical waveguide;
- (d) detecting a third polarisation state of light emerging from the end of the optical waveguide due to backscattering in a second section of the element of the optical waveguide;

(e) deducing from the first polarisation state, linear retardance δ_e and orientation of linear retardance axes q_e of the optical waveguide between the end of the optical waveguide and the element;

(f) determining the polarisation properties of the element from the second polarisation state, third polarisation state, deduced linear retardance δ_e and deduced orientation of linear retardance axes q_e ; and

(g) repeating steps (a) to (f) for plural elements of the optical waveguide to collate a spatial distribution of polarisation properties of the optical waveguide.

10 According to another aspect of the present invention, there is provided an apparatus for determining a spatial distribution of polarisation properties of an optical waveguide, the apparatus comprising:

a light source for transmitting pulses of polarised light along the optical waveguide from an end of the optical waveguide;

15 a detector for detecting a first polarisation state of light emerging from the end of the optical waveguide due to backscattering between the end of the optical waveguide and an element of the optical waveguide, a second polarisation state of light emerging from the end of the optical waveguide due to backscattering in a first section of the element of the optical waveguide,
20 and a third polarisation state of light emerging from the end of the optical waveguide due to backscattering in a second section of the element of the optical waveguide; and

a processor for deducing, from the first polarisation state, linear retardance δ_e and orientation of linear retardance axes q_e of the optical waveguide between the end of the optical waveguide and the element, determining the polarisation properties of the element from the first

5 polarisation state, second polarisation state, deduced linear retardance δ_e and deduced orientation of linear retardance axes q_e , controlling the light source and detector to repeat the transmission and detection for plural elements of the optical waveguide, repeating the deduction and determination for the plural elements of the optical waveguide and collating a spatial distribution of

10 polarisation properties of the optical waveguide from the determined polarisation properties of the plural elements.

In other words, the applicant has recognised that the complete polarisation properties of any element of an optical waveguide can be determined from these detached polarisation states of light backscattered from

15 of the optical waveguide. More specifically, the linear retardance δ_e and orientation of linear retardance axes q_e of the optical waveguide between the end of the optical waveguide and the element may be deduced from only the first polarisation state. Likewise, the polarisation properties of each element of the optical waveguide may be determined from only the second

20 polarisation state, third polarisation state, deduced linear retardance δ_e and deduced orientation of linear retardance axes q_e for the respective element.

This enables a spatial distribution of the polarisation properties of all or part of an optical waveguide to be determined straightforwardly in

comparison to CPOTDR and without significant accumulation errors. The overall length of optical waveguide to which the method and apparatus of the invention can be successfully applied is therefore significantly greater than that to which CPOTDR can be successfully applied. Indeed, the length of optical waveguide for which a spatial distribution of polarisation properties can be determined is only effectively limited by attenuation of backscattered light in the optical waveguide.

The invention is applicable to various optical waveguides. However, the optical waveguide may suitably be an optical fibre. In particular, the optical waveguide may be a mono-mode optical fibre.

The light source may transmit pulses of light having properties suitable for transmission in the particular optical waveguide under consideration. Typically, the light of the pulses may be substantially monochromatic and coherent. It may be linearly polarised. A typical wavelength of the light may be around 1550nm or in the range 1550nm to 1560nm. It may therefore be convenient for the light source to comprise a laser. A light coupler may be used to direct the transmitted light into the optical waveguide.

Complete polarisation properties of the elements of the optical waveguide can be determined. For example, the determined polarisation properties of the elements may include linear retardance δ , orientation of linear retardance axes q and circular retardance p . Alternatively, the polarisation properties of the elements or the spatial distribution of

polarisation properties of the optical waveguide can be expressed in other forms, such as a matrix or matrices, or graphically. Not all the polarisation properties of an element need therefore be calculated. The advantage of the invention lies in the ability to determine any desired polarisation properties of the optical waveguide or an element of the optical waveguide without accumulation errors.

The determination of polarisation properties of the elements can be adapted to extract the desired polarisation properties in a convenient and efficient manner. For example, by omitting calculations that relate only to undesired polarisation properties. However, where it is desired to determine the orientation of linear retardance axes q , it is preferred that this is achieved by:

repeating (a) to (d) with pulses of light having different wavelengths;
deducing values of circular retardance of the optical waveguide
between the end of the optical fibre and each element minus orientation of the linear retardances axes of the respective element, $\rho_c - q$, for the pulses of light having different wavelengths; and
extrapolating, for each element, the calculated values, $\rho_c - q$ as ρ_c tends to zero for increasing wavelength to obtain a value for orientation of the linear retardance axes q .

In other words, it is preferred that the light source transmits pulses of light having different wavelengths;

the detector detects the first, second and third polarisation states for the pulses of light having different wavelengths; and

the processor deduces values of circular retardance of the optical waveguide between the end of the optical waveguide and each element minus
5 orientation of the linear retardance axes of the respective element, $\rho_c - q$, for the pulses of light having the different wavelength and extrapolates, for each element, the calculated values, $\rho_c - q$ as ρ_c tends to zero for increasing wavelength to obtain a value for orientation of the linear retardance axes q .

This is convenient as there is no physical distinction between circular
10 retardance ρ_c of the optical waveguide between the end of the optical waveguide and each element and orientation of the linear retardance axes q of the respective element. It is therefore more straightforward to extrapolate orientation of the linear retardances axes q by determining circular retardance of the optical waveguide between the end of the optical waveguide and each
15 element minus orientation of the linear retardance axes of the respective element, $\rho_c - q$, for different wavelengths of light.

The different wavelengths of light of the light pulses may be selected as desired. Preferably, at least these different wavelengths, or three pulses having different wavelengths of light, are transmitted for each element in
20 order to provide accurate extrapolation. In particular, pulses having wavelengths of light varying from 1500nm to 1560nm may be transmitted for each element. The light source may therefore conveniently comprise a turnable laser.

The first polarisation state may be that of light emerging from the end of the optical waveguide due to backscattering substantially half way between the end of the optical waveguide and the element. Alternatively, the first polarisation state may be that of light emerging from the end of the optical waveguide due to backscattering substantially at an end of the element closest to the end of the optical waveguide into which the light pulses are transmitted.

The first and second sections may be substantially adjacent. They may be substantially equal in length along the major axis of the optical waveguide. Indeed, the first and second sections of the element may together define the element.

Preferred embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a perspective view of an optical waveguide;

Figure 2 is a longitudinal, sectional view of the optical waveguide of figure 1;

Figure 3 is a transverse, sectional view of the optical waveguide of figure 1;

Figure 4 is an illustration of two modes of polarisation of light;

Figure 5 is a longitudinal, sectional view of an optical waveguide illustrating Polarisation Optical Time Domain Reflectometry;

Figure 6 is a longitudinal, sectional view of an optical waveguide illustrating Computational Polarisation Optical Time Domain Reflectometry;

Figure 7 is a longitudinal, sectional view of an optical fibre illustrating a method of determining the spatial distribution of polarisation properties of an optical fibre according to the invention;

Figure 8 is a graphical illustration of a determination of orientation of linear retardance axes q according to the invention;

Figure 9 is a schematic illustration of an apparatus for determining the spatial distribution of polarisation properties of an optical fibre according to the invention; and

Figure 10 is an illustration of an optical fibre arranged for temperature measurement according to the invention.

The invention is applicable to various types of waveguide and in particular to any optical waveguide that provides mono-mode transmission of light. Whilst the examples, below are described with reference to an optical fibre, these examples can be extended to application in other optical waveguides when applicable.

Referring to Figures 1 to 3, an optical fibre 1 is an optical fibre comprising a core 2, which might be cylindrical and made from silica (i.e. glass) or another highly optically transmissive material, and a cladding 3 which generally encloses the circumference of the core 2 along the length of the optical waveguide 1. A typical diameter D for the optical fibre 1 might be $100\mu\text{m}$. The core 2 has a refractive index n_{cr} and the cladding 3 has a refractive index n_{cl} . The refractive index n_{cr} of the core 2 is greater than the refractive index n_{cl} of the cladding 3, i.e. $n_{\text{cr}} > n_{\text{cl}}$, such that light passing

generally along the length of the core 2 is totally internally reflected in the core 2 at a boundary 4 between the core 2 and cladding 3.

In this example, the geometry and refractive indices n_{cr} and n_{cl} of the core 2 and cladding 3 are selected such that only one reflection angle θ at the boundary 4 between the core 2 and cladding 3 results in the propagation of light of wavelength λ along the optical fibre 1. More specifically,

$$\frac{\pi D}{\lambda} (n_{cr}^2 - n_{cl}^2)^{1/2} \leq 2.405$$

Such an optical fibre 1 is said to transmit light of wavelength λ in a "single-mode" or "mono-mode". This is well known in the art and the features of such fibres will not therefore be described in detail.

One characteristic of such mono-mode propagation of light is that, at any point along the length of the optical fibre 1, light has a single polarisation state. In other words, due to the propagation characteristics of the optical fibre 1, light passing from one point along the length of the optical fibre 1 to another point along the length of the optical fibre 1 travels substantially the same distance. This has the result that the polarisation state of light at any given point along the optical fibre 1 is singular and definite rather than comprised of plural polarisation states.

However, the polarisation state of light varies from point to point along the length of the optical fibre 1 due to the polarisation properties of the optical fibre 1. In an ideal optical fibre, the change in polarisation of light as it passes along the fibre might be constant. In practice, the change in polarisation of light as it passes along the optical fibre 1 varies and is

dependent on a number of factors. In particular, bends, twists and inhomogeneities in the optical fibre 1 and in particular the shape of the core 2 cause varying changes in polarisation. External influences, such as stress, magnetic fields, electric fields and radiation, can also affect the change in polarisation of light passing along the optical fibre 1.

In more detail, light propagates along a mono-mode optical fibre with two polarisation modes, which may be thought of as orthogonal ellipses 5, 6, for example as illustrated in Figure 4. Each ellipse 5, 6 is effectively the locus of points mapped by the electric field vector of light propagating in the respective mode over a single wavelength of the light. As light propagates along the mono-mode optical fibre 1, the shape of the ellipses changes due to the polarisation properties of the optical fibre 1.

One polarisation property exhibited by the optical fibre 1 is linear birefringence. Linear birefringence may result from, *inter alia*, the core 2 not being perfectly circular. In other words, slight ellipticity of the core 2 can result in linear birefringence. Linear birefringence can be thought of as causing the major axes of the ellipses 5, 6, i.e. the linear polarisation component of each polarisation mode, to propagate at different velocities. This results in the generation of a phase difference between the linear polarisation component of each polarisation mode over a given length of the optical fibre 1, which phase difference is referred to as linear retardance δ . In order to fully define the linear birefringence of the optical fibre 1, it is also necessary to consider by how much the major axis of at least one of the

ellipses 5, 6 or linear polarisation components of the polarisation modes rotate over a given length of the optical fibre 1 and this is referred to as the orientation of linear retardance axes q .

Another polarisation characteristic exhibited by the optical fibre 1 is
5 circular birefringence. Circular birefringence may result from, *inter alia*, axial twists in the core 2. Circular birefringence can be thought of as causing the degree of ellipticity of the ellipses 5, 6, i.e. the circular component of the each polarisation mode, to propagate along the optical fibre at different velocities. The difference in the velocity of propagation of the circular
10 components of each polarisation mode is referred to as circular retardance p .

Linear retardance δ , orientation of the linear retardance axes q and circular retardance p fully define the polarisation properties of a given length of the optical fibre 1. It is therefore desired to be able to determine these parameters in order to assess the polarisation properties of the optical fibre 1.

15 In the prior art, Polarisation Optical Time Domain Reflectometry (POTDR) has been used with some success to measure the polarisation properties of a mono-mode optical fibre. Such a method is described in "Polarisation Optical Time Domain Reflectometry", Rogers, A.J., Electronics Letters, 19 June 1980, Vol 16, No. 13, pp 489-490.

20 Briefly, referring to Figure 5, a pulse 7 of light is transmitted along the optical fibre 1 (in a forward direction) by transmitting the pulse 7 of the light into the optical fibre at end 8 of the optical fibre 1. As the pulse 7 of light passes along the optical fibre 1 small imperfections or inhomogeneities in the

optical fibre 1 cause the light to be reflected or scattered according to Rayleigh's Law. Some of this scattered light returns along the optical fibre 1, emerges from the end 8 of the optical fibre 1 and can be detected. Rayleigh scattering does not affect the polarization of the light and the light returning
5 along the fibre therefore carries information regarding the polarization characteristics of the optical fibre 1 up to the point at which the scattering took place.

Light backscattered at a first axial position A along the optical fibre 1 will return to the end 8 of the optical fibre 1 at a first time t_1 . Light reflected
10 at a second axial position B along the optical fibre 1 will return to the end 8 of the optical fibre 1 at a second, later time t_2 . Thus, by analysing the polarization state of light emerging from the end 8 of the optical fibre 1 at the first and second times t_1 , t_2 , information regarding the polarization properties of the optical fibre 1 between the points A and B can be determined.

15 However, whilst linear birefringence is independent of the direction in which light is travelling along the optical fibre 1, circular birefringence is not. Indeed, circular birefringence in one direction along the optical fibre 1 is equal and opposite to circular birefringence in the opposite direction along the optical fibre 1. This has the result that circular birefringence acting on light
20 backscattered at any point along the optical fibre 1 cancels the circular birefringence acting on light incident at that point. Thus, POTDR is only able to identify parameters relating to linear birefringence in monomode optical

fibres or, in other words, is only able to identify linear retardance δ and the orientation of the linear retardance axes q .

Computational Polarization Optical Time Domain Reflectometry (CPOTDR) was developed in order to overcome this limitation. CPOTDR is
5 described, for example, in "Computational Polarization-Optical Time Domain Reflectometry for Measurement of the Spatial Distribution of PMD in Optical Fibres", Rogers A.J., Zoo Y.R. and Handrack V.A., Proc.OFMC '97, September 1997, pp126-129.

Briefly, referring to Figure 6, in CPOTDR, the optical fibre 1 is
10 considered as a series of elements Z_1 to Z_i in Figure 6, with element Z_1 being adjacent the end 8 of the optical fibre 1. The elements Z_1 to Z_i each have the same axial length along the optical fibre 1 and are adjacent one another. Each element 9 has linear retardance δ_i orientation of linear retardance axes q_i and circular retardance ρ_i . Pulses 7 of light are transmitted along the optical fibre
15 1 (in a forward direction) and the backscattered light analysed in a manner similar to POTDR.

In CPOTDR, the elements Z_1 to Z_i are effectively divided into two equal sections 10, 11. The polarisation state of light backscattered in each section of each element Z_1 to Z_i is detected at end 8 of the optical waveguide
20 1, as illustrated in Figure 6. A Jones matrix can be used to describe the polarisation properties of each element Z_1 to Z_i of the optical waveguide 1. The change of polarisation of light propagating forward and then backscattered through each section 10, 11 of each element Z_1 to Z_i is

determined by the product of the relevant Jones matrices. Starting from the end 8 of the optical section 1, these successive products are shown as:

$$\begin{aligned}
 & M_1^T M_1 \\
 & (M_1 M_1')^T (M_1 M_1') \\
 5 \quad & (M_2 M_1 M_1')^T (M_2 M_1 M_1') \\
 & (M_2 M_2' M_1 M_1')^T (M_2 M_2' M_1 M_1') \\
 & : \\
 & (M_i M_i' \dots M_1 M_1')^T (M_i M_i' \dots M_1 M_1') \\
 & = M_1^T M_1'^T \dots M_i'^T M_i^T M_i M_i' \dots M_1' M_1
 \end{aligned} \tag{1}$$

10

Where M_i is the Jones matrix of the first section 10 of each element Z_i and M_i^T is its transpose and M_i' is the Jones matrix of the second section 11 of each element Z_i and $M_i'^T$ its transpose. These matrix products can be derived from detection of the polarisation characteristics of backscattered light emerging from end 8 of the optical fibre 1. The Jones matrix for an element Z_1 to Z_i with both linear and circular birefringence has the form:-

15

$$M = \begin{pmatrix} \alpha + i\beta \cos(2q) & -\gamma + i\beta \sin(2q) \\ \gamma + i\beta \sin(2q) & \alpha - i\beta \cos(2q) \end{pmatrix}$$

$$\text{where } \alpha = \cos \Delta, \beta = \frac{\delta}{2} \left(\frac{\sin \Delta}{\Delta} \right), \gamma = P \frac{\sin \Delta}{\Delta}$$

$$\text{with } \Delta = \left(\rho^2 + \frac{\delta^2}{4} \right)^{1/2} \text{ and } \alpha^2 + \beta^2 + \gamma^2 = 1 \tag{2}$$

20

The product of the form $M^T M$ is equivalent to a linear retarder and has the general form:-

$$\begin{pmatrix} A+iB & iC \\ iC & A-iB \end{pmatrix}$$

where

$$A^2 + B^2 + C^2 = 1$$

$$A = \alpha^2 + \gamma^2 - \beta^2$$

$$5 \quad B = 2\beta(\alpha \cos(2q) - \gamma \sin(2q))$$

$$C = 2\beta(\alpha \sin(2q) + \gamma \cos(2q)) \quad (3)$$

In equations (3), we see that there are only two independent equations for the three unknowns. However, as mentioned before, each element is effectively divided into two sections 10, 11. When the product $M_i^T M_i$ for the first section and $M_i'^T M_i'$ for the second section 11 of an element Z_i are known, equations (3) show that four independent equations are then available for the three parameters δ_i , q_i and ρ_i . By solving these equations, the Jones matrix of the element Z_i can be found. In other words δ_i , q_i and ρ_i can be determined.

However, from equations (1) it is seen that only for the first element Z_1 are the products $M_1^T M_1$ and $(M_1 M_1')^T (M_1 M_1')$ obtained directly. For the succeeding elements Z_i , the products for each element Z_i are obtained by using the calculated Jones matrices for the preceding elements Z_1 to Z_{i-1} . Therefore, the accuracy of the calculated parameters δ_i , q_i and ρ_i depends on the calculation accuracy of the parameters for the preceding elements Z_1 to Z_{i-1} .

Referring to Figure 7, in a method of determining the spatial distribution of polarization characteristics of the optical fibre 1 according to the invention, the optical fibre 1 is considered as a series of discrete elements R in which the polarization properties of the optical fibre 1 are considered to be homogenous. Each element R is, in turn, considered as two adjacent sections R1, R2 of equal size, although in other examples, the elements R may be divided into a different number or other size sections as desired. The element R is considered to have polarization characteristics, to be determined, comprising linear retardance δ , orientation of the linear retardance axes q and circular retardance p . In addition, the portion e of the optical fibre between the end 8 of the optical fibre 1 and the element R under consideration or, more specifically, between the end 8 of the optical fibre 1 and the boundary of the element R closest to the end 8 of the optical fibre 1, is considered to have linear retardance δ_e , orientation of the linear retardance axes q_e and circular retardance p_e .

Conveniently, the portion e of the optical fibre 1 can be considered as a retarder-rotator pair. In other words, half of the portion e can be considered to have polarization properties comprising only the linear retardance δ_e and orientation of the linear retardance axes q_e and the other half of the portion e can be considered to have polarization properties comprising only circular retardance p_e . Furthermore, light that passes along the path AC to the element R can be considered to have linear retardance δ_e and orientation of the linear retardance axes q_e equivalent to light that passes along the passage ABA, i.e.

is backscattered at B, halfway along portion e. The linear retardance δ_e of portion e and the orientation of the linear retardance axes q_e of portion e can therefore be measured directly from the polarisation state of light backscattered from point B to the end 8 of the optical fibre 1. In another
 5 example, the linear retardance δ_e of the position e and the orientation of the linear retardance axes q_e of portion e can be deduced directly from the polarisation state of light backscattered from point e to the end 8 of the optical fibre 1.

It therefore remains for the linear retardance δ , orientation of the linear
 10 retardance axes q and circular retardance ρ of the portion e, along with the circular retardance ρ_e of the portion e to be determined. As for CPOTDR, it is possible to derive the Jones matrix products $M_{R1}^T M_{R1}$ and $M_{R2}^T M_{R2}$ from detection of the polarisation state of backscattered light emerging from the end of the optical waveguide 1. Equations (3) therefore show that we from
 15 $M_{R1}^T M_{R1}$ and $M_{R2}^T M_{R2}$ have four independent equations for the four parameters δ , q , ρ and ρ_e . By solving these equations, the Jones matrix M_R of element R and δ , q , ρ and ρ_e can be found.

However, there is no physical distinction between circular retardance ρ_e and orientation of the linear retardance axes q , and $Q = (\rho_e - q)$ is the
 20 parameter that is directly calculable, although, in other examples, $(\rho_e + q)$ might be calculated. Circular retardance ρ_e depends on the wavelength λ of light, whilst orientation of the linear retardance axes q does not. Furthermore, circular retardance $\rho_e(\lambda)$ decreases to zero as wavelength λ increases to

infinity. Referring to figure 8, it is therefore possible to calculate $Q(\lambda)$ for light pulses of different wavelengths λ and extrapolate a value for orientation of the linear retardances axes q .

Referring to figure 9, an apparatus 100 for determining the spatial
5 distribution of polarisation properties of an optical fibre comprises a light source 12, which, in this example, is a tunable laser able to transmit polarised, coherent light of any desired wavelength between 1550nm and 1560nm. Light transmitted by the light source 12 is directed into a beamsplitter 13. The beamsplitter 13 transmits some of the light incident on it from the light
10 source 12 to an optical coupler 14, in this example by admitting the light to pass straight through the beam splitter 13. Some of the light incident from the light source 12 is also transmitted to a polarisation analyser 15, in this example by reflecting the light through an angle of 90°.

The optical coupler 14 passes light incident on it from the beamsplitter
15 13 into the optical fibre 1 through the end 8 of the optical fibre 1. The optical coupler 14 also transmits light emitted from the end 8 of the optical fibre 1, for example by backscattering in the optical fibre 1, to the beamsplitter 13. This emitted, e.g. backscattered, light is re-directed by the beamsplitter 13 to the polarisation analyser 15.

20 The polarisation analyser 15 comprises a Stokes analyser.
More specifically, the polarisation analyser 15 has a four optical elements arranged in the path of the light re-directed from the beamsplitter 13. The optical elements comprise, in series, a first linear polariser, a second linear

polariser arranged at 45° to the first linear polariser, a quarter wave plate, i.e. an optical element that retards light by quarter of a wavelength, and a third linear polariser arranged at the same orientation as the second linear polariser. Light emerging from each of the linear polarisers is incident on a photodetector 16, such as photodiode array. Thus, the intensity of the light of each polarisation state separated by the linear polarisers is detected by the photodetector 16.

The intensity information is output by the photodetector 16 to a processor 17, such as the Central Processing Unit (CPU) of a Personal Computer (PC). The processor 17 is able to formulate the output of the photodetector 16 in the Stokes Formalism which represents the polarisation state of light emitted from the end 8 of the optical fibre 1. The Stokes Formalism allows a Mueller matrix of the general form:

$$M_{\Gamma} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & A_R^2 + B_R^2 - C_R^2 & 2B_R C_R & -2A_R C_R \\ 0 & 2B_R C_R & A_R^2 + C_R^2 - B_R^2 & 2A_R B_R \\ 0 & 2A_R C_R & -2A_R B_R & -A_R^2 - B_R^2 - C_R^2 \end{pmatrix}$$

It is possible to determine the Jones matrices and linear retardance δ orientation of linear retardance axes q and circular retardance p from the Mueller matrices of light backscattered in the optical fibre 1 as set out above.

The processor 17 is connected to a light source controller 18 for controlling the light source 12. The light source controller 18 is operable to select the wavelength at which light is transmitted by the light source 12 and the light pulse 7 timing and duration. The timing and duration of the light pulses 7 transmitted by the light source 12 can be verified by the processor 17 from the output of the photodetector 16 corresponding to light transmitted from the beamsplitter 13 to the polarisation analyser 15 from light incident on the beamsplitter 13 from the light source 12.

The timing and duration of the pulses 7 of light emitted by the light source 18 controlled, in combination with the time at which the output of the photodetector 16 is analysed, to resolve light backscattered in appropriate parts of the optical fibre 1, as described above. Thus, different elements R of the optical fibre 1 can be resolved.

The output of the processor 17 is transmitted to an output device 19 which, in this example, is a display such as an oscilloscope or other Cathode Ray Tube (CRT) monitor. The output is indicative of the determined polarisation properties at the optical fibre 1.

In a first example, the apparatus 100 is adapted to measure Polarisation Mode Dispersion in a telecommunications system. The optical coupler 14 is adapted to transmit light into telecommunications optical fibres for testing, either in situ or during or after manufacture.

The output is indicative of a spatial distribution of PMD along the fibre on test and enables fibres or part of fibres having anomalously large PMD to be identified and, e.g., discarded.

5 In a second example, referring to figure 10, the optical fibre 1 is wound into a uniform helix. The strain along the length of the optical fibre 1 is therefore substantially uniform. The apparatus 100 is adapted to measure the spatial distribution of polarisation properties of the optical fibre 1 from time to time. The change in the distribution of polarisation properties of the optical fibre 1 is indicative of changes in strain in respective parts of the fibre
10 which, in turn, is indicative of changes in temperature at those parts causing thermal expansion or contraction of the optical fibre. Thus, after calibration, the apparatus 100 is able to output a spatial distribution of temperature along the length of the optical fibre 1.

Changes in bending of the optical fibre 1 generally cause changes in
15 linear retardance δ and orientation of linear retardances axes q . Changes in twisting of the optical fibre 1 generally causes changes in circular retardance ρ . In another example, the apparatus 100 therefore correlates linear retardance δ and orientation of linear retardance axes q with circular retardance to provide a more accurate spatial distribution of temperature along
20 the length of the optical fibre 1.

In "Optical-Fibre Current Measurement", Rogers, A.J., Optical-Fibre Sensing Technology, Chapman and Hall (Edited by Grattan and Meggitt) 1995, Chapter 13B pp 421-440, a method of measuring current flowing

through a loop of optical fibre is described. In another example of the invention, the apparatus 100 is adapted to improve this technique.

In this example, the optical fibre 1 is formed in a loop with an electric current to be measured passing axially through the loop. This arrangement
5 results in the magnetic field generated by the electric current passing along the loop of optical fibre 1 axially. This induces a non-reciprocal circular retardance ρ in the optical fibre 1 by the Faraday magneto-optic effect.

Measurement of circular retardance ρ therefore provides a measurement of current. However, in the prior art, vibrationally-induced
10 linear retardance δ and orientation of linear retardances axes q interfere with measurement of circular retardance ρ . The spatial distribution of polarisation properties output by the apparatus 100 can separate linear retardance δ and orientation of linear retardance axes q from circular retardance ρ and a more accurate measurement of current is therefore produced.

15 In yet another example, the optical fibre 1 is arranged such that an electric field induces a linear birefringence in this optical fibre 1. The apparatus 100 determines a spatial distribution of the polarisation properties of the optical fibre 1 that is indicative of the electric field acting on the fibre. Integration of the electric field between two points along the fibre yields a
20 measurement of voltage between the two points. Vibrational effects can be discriminated against by knowledge of the electric field direction(s) or frequency discrimination. In combination with the example set out above, both electric current and electric voltage can be measured by apparatus 100.

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In another example, the optical fibre 1 is arranged to undergo the same strain as a structure, the strain on which it is desired to measure. For example, the optical fibre 1 may be embedded in a reinforced concrete slab of a building or bridge. As strain on the optical fibre 1 changes the spatial
5 distribution of polarisation properties of the optical fibre 1, measured by apparatus 100, changes. Thus, a spatial distribution of the strain or stress on the structure can be determined.

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CLAIMS

1. A method of determining a spatial distribution of polarisation properties of an optical waveguide, the method comprising:
 - (a) transmitting pulses of polarised light along the optical waveguide
 - 5 from an end of the optical fibre;
 - (b) detecting a first polarisation state of light emerging from the end of the optical waveguide due to backscattering in the optical waveguide between the end of the optical waveguide and an element of the optical waveguide;
 - (c) detecting a second polarisation state of light that emerges from the
 - 10 end of the optical waveguide due to backscattering in a first section of the element of the optical waveguide;
 - (d) detecting a third polarisation state of light that emerges from the end of the optical waveguide due to backscattering in a second section of the element of the optical waveguide;
 - (e) deducing, from the first polarisation state, linear retardance e and
 - 15 orientation of linear retardance axes q_e of the optical waveguide between end of the optical waveguide and the element;
 - (f) determining the polarisation properties of the element from the second polarisation state, third polarisation state, deduced linear retardance e
 - 20 and deduced orientation of linear retardance axes q_e ; and
 - (g) repeating steps (a) to (f) for plural elements of the optical waveguide to collate a spatial distribution of polarisation properties of the optical waveguide.

2. The method of claim 1, wherein the determined polarisation properties of the elements include linear retardance δ , orientation of linear retardance axes q and circular retardance ρ of the elements.
3. The method of claim 1 or claim 2, wherein the optical waveguide is an
5 optical fibre.
4. The method of any one of claims 1 to 3, wherein the optical waveguide is a mono-mode optical fibre.
5. The method of any one of claims 1 to 4, wherein the determination of polarisation properties of the elements includes determination of orientation
10 of linear retardance axes q of the elements by:
 repeating (a), (b), (c) and (d) with pulses of light each having different wavelengths;
 deducing values of circular retardance of the optical waveguide between the end of the optical waveguide and each element minus orientation
15 of the linear retardance axes of the respective element, $\rho_e - q$, for the pulses of light having different wavelengths; and
 extrapolating the calculated values, $\rho_e - q$, as ρ_e tends to zero for increasing wavelength to obtain a value for orientation of the linear retardance axes q of each element.
- 20 6. The method of any one of the preceding claims, wherein the first detected polarisation state is that of light backscattered substantially half way between the end of the optical waveguide and the element.

7. The method of any one of claims 1 to 5, wherein the first detected polarisation state is that of light backscattered substantially at the end of the element closest to the end of the optical waveguide.
8. The method of any one of the preceding claims, wherein the first and
5 second sections of the element are substantially adjacent.
9. The method of any one of the preceding claims, wherein the first and second sections of the element are substantially equal in length along the major axis of the optical waveguide.
10. The method of any one of the preceding claims, wherein the first and
10 second sections of the element together define the element.
11. An apparatus for determining a spatial distribution of polarisation properties of an optical waveguide, the apparatus comprising:
a light source for transmitting pulses of polarised light along the optical waveguide from an end of the optical waveguide;
15 a detector for detecting a first polarisation state of light emerging from the end of the optical waveguide due to backscattering in the optical waveguide between the end of the optical waveguide and an element of the optical waveguide, a second polarisation state of light that emerges from the end of the optical waveguide due to backscattering in a first section of the
20 element of the optical waveguide, and a third polarisation state of light that emerges from the end of the optical waveguide due to backscattering in a second section of the element of the optical waveguide; and

a processor for deducing, from the first polarisation state, linear retardance ρ_e and orientation of linear retardance axes q_e of the optical waveguide between end of the optical waveguide and the element, determining the polarisation properties of the element from the first polarisation state, second polarisation state, deduced linear retardance ρ_e and deduced orientation of linear retardance axes q_e , controlling the light source and detector to repeat the transmission and detection for plural elements of the optical waveguide, repeating the deduction and determination for the plural elements of the optical waveguide and collating a spatial distribution of polarisation properties of the optical waveguide.

12. The apparatus of claim 9, wherein:

the light source transmits pulses of light each having different wavelengths;

the detector detects the first, second and third polarisation for the pulses of light of different wavelengths; and

the processor deduces values of circular retardance of the optical fibre between the end of the optical fibre and the element minus orientation of the linear retardance axes of the element, $\rho_e - q$, for the pulses of light of each different wavelength and extrapolates the calculated values, $\rho_e - q$, as ρ_e tends to zero for increasing wavelength to obtain a value for orientation of the linear retardance axes q of each element.

13. A method of determining Polarisation Mode Dispersion (PMD) in an optical fibre comprising the method of any one of claims 1 to 10.

14. An apparatus for determining Polarisation Mode Dispersion in an optical fibre comprising the apparatus of claim 11 or claim 12.

15. A method of determining changes in the polarisation properties of an optical fibre due to external influences, the method comprising the method of
5 any one of claims 1 to 10.

16. An apparatus for determining changes in the polarisation properties of an optical fibre due to external influences, the apparatus comprising the apparatus of claim 11 or claim 12.

17. Computer software adopted to carry out the method of any one of
10 claims 1 to 10, 13 or 15.

18. An apparatus substantially as described with reference to any one of figures 1 to 4 or 7 to 10 of the accompanying drawings.

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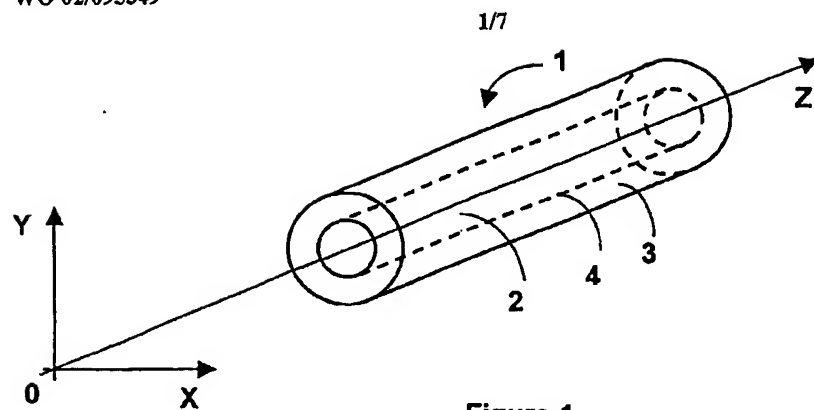


Figure 1

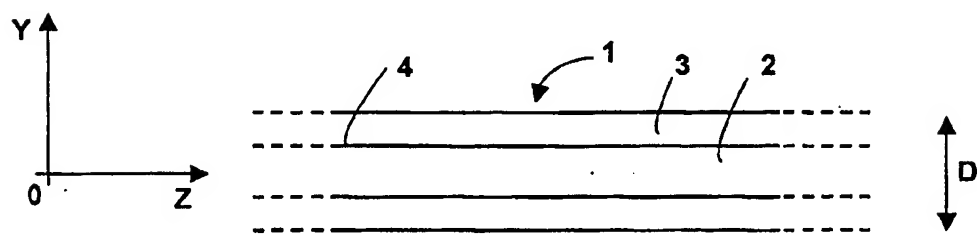


Figure 2

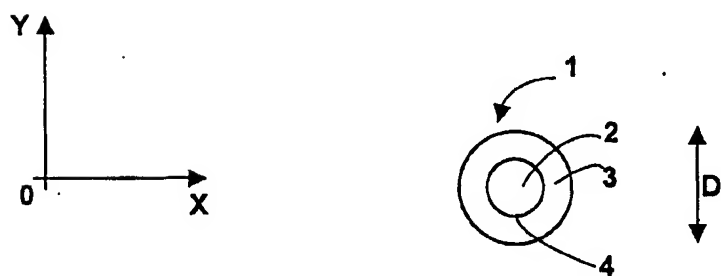


Figure 3

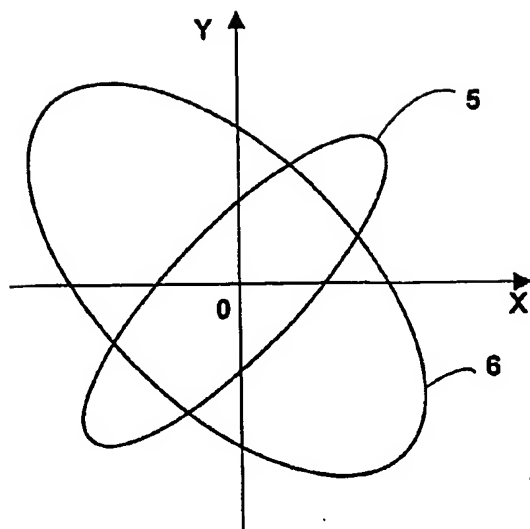


Figure 4

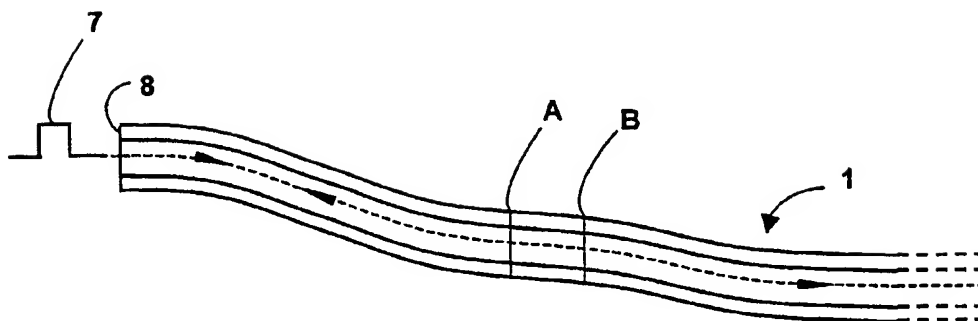


Figure 5

Prior Art

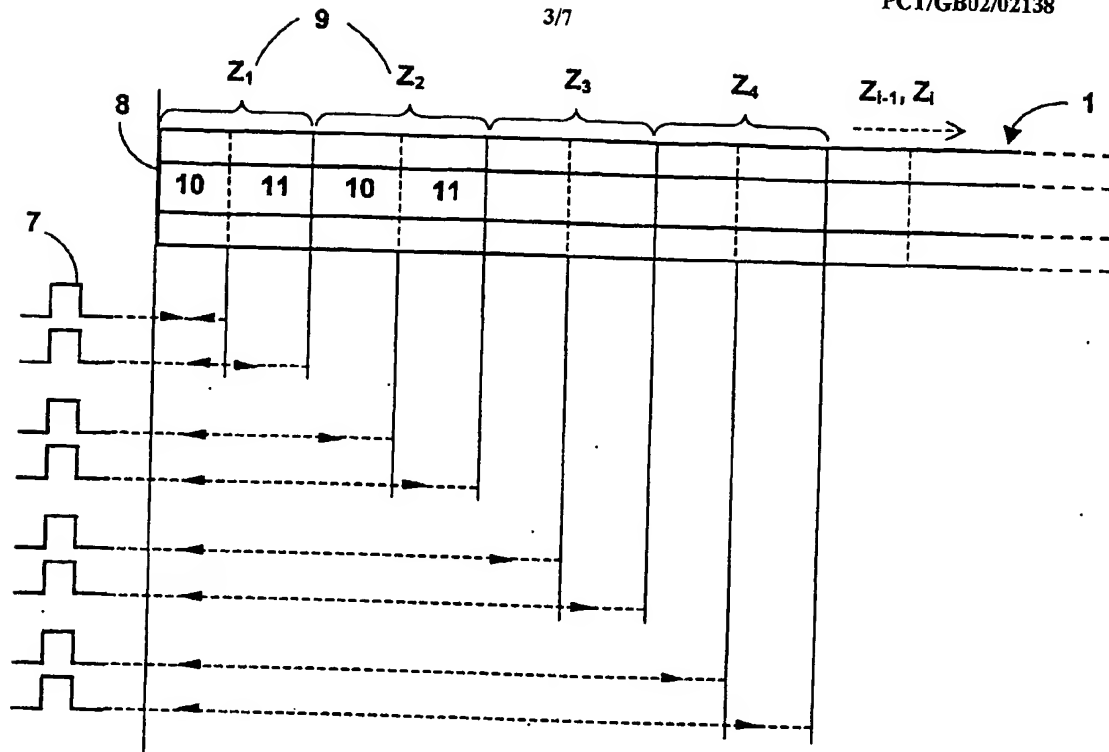
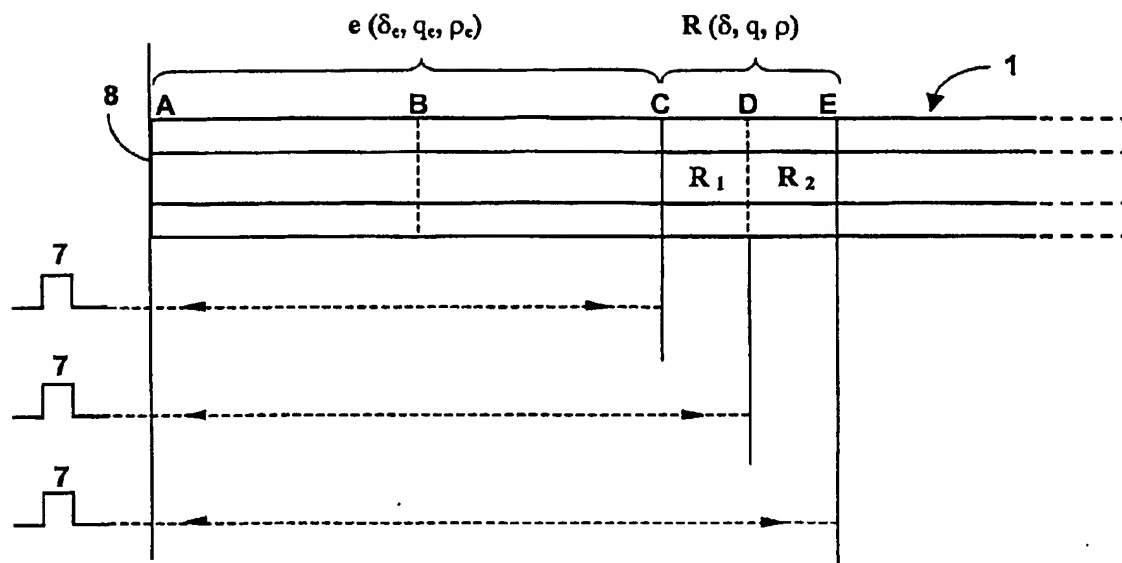


Figure 6

Prior Art

**Figure 7**

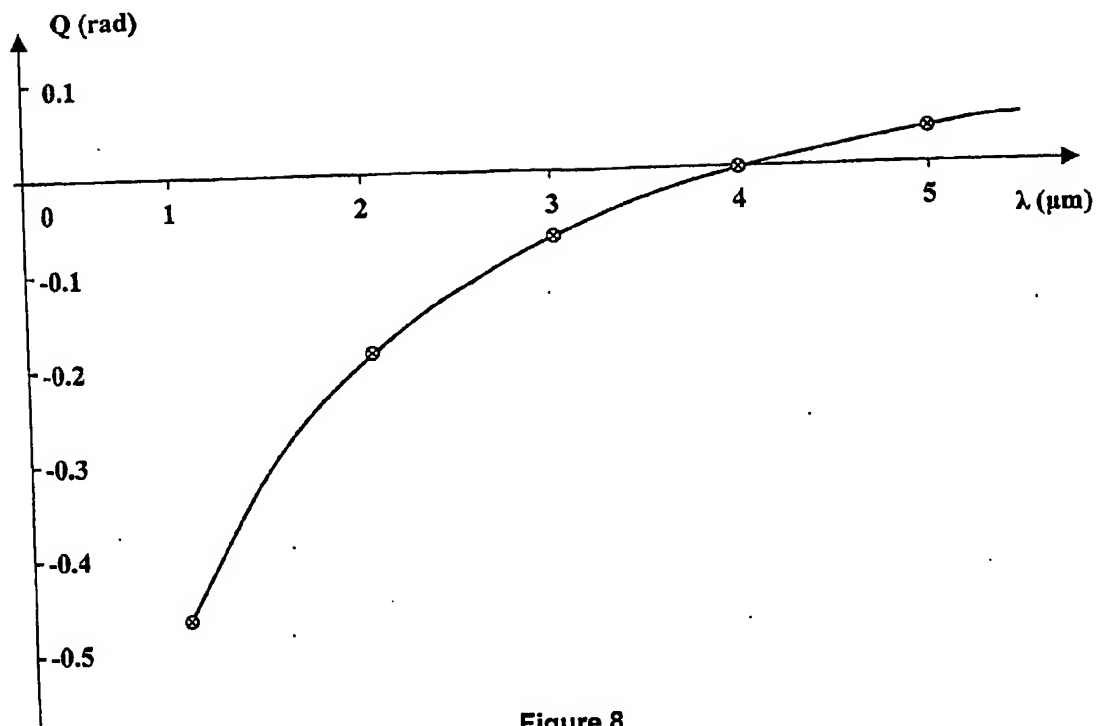


Figure 8

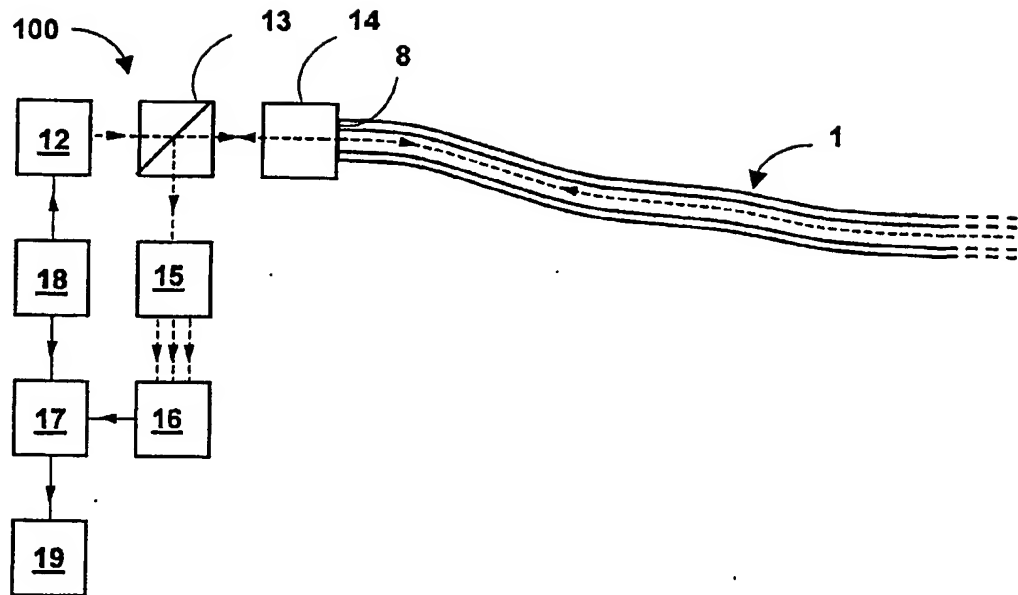
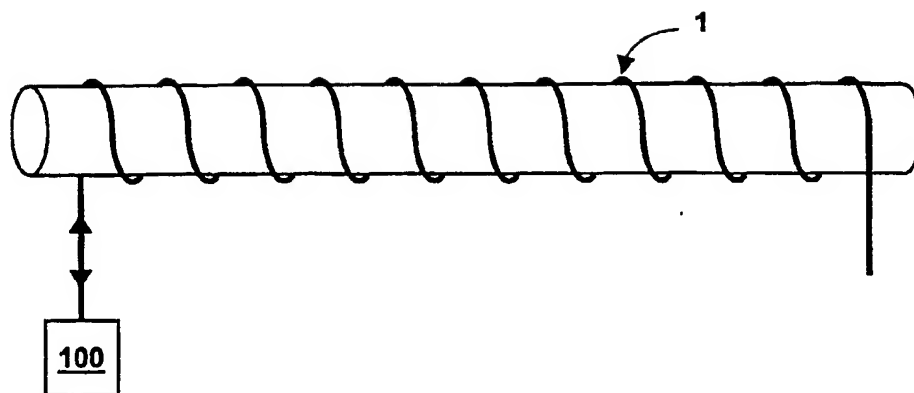


Figure 9

**Figure 10**

INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01M11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

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IPC 7 G01M

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Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>ROGERS A J: "Polarisation optical time domain reflectometry"</p> <p>ELECTRONICS LETTERS, 19 JUNE 1980, UK, vol. 16, no. 13, pages 489-490, XP001097960</p> <p>ISSN: 0013-5194</p> <p>cited in the application</p> <p>the whole document</p> <p style="text-align: center;">-/-</p>	1,11,17

☒ Further documents are listed in the continuation of box C.

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Gerken, S

INTERNATIONAL SEARCH REPORT

In International Application No
PCT/GB 02/02138

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>ROGERS A J ET AL: "Computational polarization-optical time domain reflectometry for measurement of the spatial distribution of PMD in optical fibres"</p> <p>OFMC '97. 4TH OPTICAL FIBRE MEASUREMENT CONFERENCE. CONFERENCE DIGEST, OFMC '97. 4TH OPTICAL FIBRE MEASUREMENT CONFERENCE. CONFERENCE DIGEST, TEDDINGTON, UK, 29 SEPT.-1 OCT. 1997, pages 126-129, XP001099042</p> <p>1997, Teddington, UK, NPL, UK</p> <p>ISBN: 0-946754-19-5</p> <p>cited in the application</p> <p>the whole document</p>	1
X	<p>ROGERS A J: "Distributed measurement of strain using optical-fibre backscatter polarimetry"</p> <p>STRAIN, AUG. 2000, BRITISH SOC. STRAIN MEAS, UK, vol. 36, no. 3, pages 135-142, XP001095728</p> <p>ISSN: 0039-2103</p> <p>the whole document</p>	1-4, 6-11, 13-17
A	<p>ELLISON J G ET AL: "A FULLY POLARIMETRIC OPTICAL TIME-DOMAIN REFLECTOMETER"</p> <p>IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE INC. NEW YORK, US, vol. 10, no. 2, 1 February 1998 (1998-02-01), pages 246-248, XP000733818</p> <p>ISSN: 1041-1135</p> <p>the whole document</p>	1,11,17

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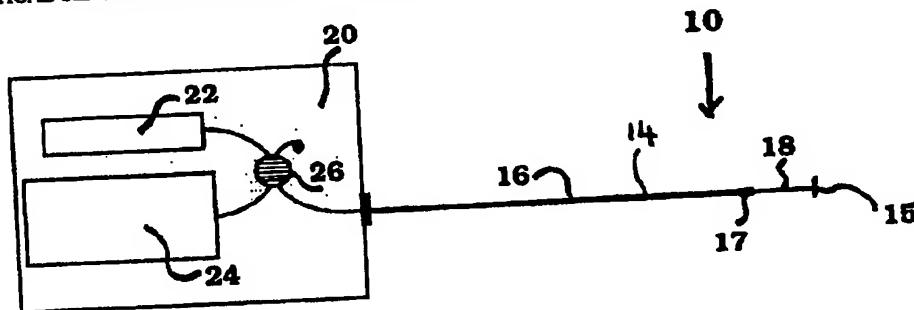
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Published
With international search report.

(54) Title: **OPTICAL SENSORS AND METHOD FOR PRODUCING FIBRE OPTIC MODALMETRIC SENSORS**



(57) Abstract

An optical sensor and a method of producing the optical sensor is disclosed in which a singlemode fibre (14) is fusion spliced to a multimode fibre (18). The multimode fibre is cleaved or polished at a desired location from the splice (17) to localise the sensor, the end (15) of the multimode fibre can be mirrored to reflect radiation back through the multimode fibre so that the radiation re-enters the singlemode fibre for detection by a detector (24). Alternatively, a light source (22) can be coupled to the singlemode fibre and a further singlemode fibre connected to the multimode fibre at the desired location by fusion splicing so that a detector (24) can be connected to the further singlemode fibre for detecting radiation which is passed through the multimode fibre and which has had its property changed in the multimode fibre.

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- 1 -

OPTICAL SENSORS AND METHOD FOR PRODUCING FIBRE OPTIC
MODALMETRIC SENSORS

This invention relates to an optical sensor and method for producing modalmetric waveguide sensors.

5 Optical devices are commonly used in industry and science and include laser cavities, waveguides, lenses and other optical elements. Such optical devices are used in a variety of instruments and installations.

10 Photonics technology has revolutionised the communications and sensor fields. This is mainly due to the rapid development of opto-electronic devices. A wide variety of glass materials, material-dopants and waveguide structures are available and the present invention relates to a waveguide sensor which is particularly well suited for
15 detecting and monitoring structural parameters caused by acoustic, mechanical, electrical and magnetic events (i.e. strain, vibration, resonance, acoustic emission, etc.). In particular, the fibre optic modalmetric sensor has been proven to have good potential for vibrational analysis of
20 structures and for machine condition monitoring applications.

 Presently, there is a very high demand for sensors and systems which provide real-time monitoring of the integrity or condition of machines and structures.
25 Fibre optic sensors, in particular, are very promising for these applications because of their dielectric properties, their fine size, their ability to be remotely located and, in the case of intrinsic sensors, rapid response times. They also have particular advantages in hazardous
30 environments. In addition, they have several clear advantages over existing conventional sensing techniques such as bulk optical measurements, potentiometric electrodes, resistive foil gauges and piezo-electric transducers.

35 Engineer d structures are usually not monitored in real-time because of the difficulties in incorporating

- 2 -

th sensors into the sensing environment and because of th limitations of the sensors. Optical sensors overcome these difficulties by virtue of their inherent properties. In addition, optical sensors and optical processing systems
5 are extremely fast and do not suffer from electro-magnetic interference (EMI), unlike their electronic counter-parts.

A simplistic definition of the modes that are guided by an optical fibre can be explained as the locus of all the light rays which are launched at different entry
10 angles into the core of the fibre. For any optical fibre the number of modes that will be guided by the fibre is dependent on core size, the ratio of core/cladding refractive indices, and the wavelength of operation.

Multimode optical fibres suffer from optical
15 signal fading and drift due to the random or chaotic nature of the light propagating along the fibre. The optical fibre industry has overcome the inherent weaknesses of multimode fibres by the use of singlemode fibre systems, but these are difficult to handle, and utilise quite
20 expensive components.

The claimed invention overcomes the inherent weaknesses of multimode fibre optic sensors, is easy to fabricate and costs relatively little to assemble.

Optical fibres were found to be very microphonic
25 quite early in the development of fibre optic systems. [Culshaw et al., "Acoustic Sensitivity of Optical Fibre Waveguides", *Electronic Letters*, 13(25), pp. 760-761, 1977] In the simplest configuration, a source of coherent optical radiation is used to launch light into a multimode fibre
30 and a photodetector monitors the transmitted output signal. Loads, vibrations and acoustic signals acting on the multimode fibre causes a change in length, diameter, and refractive index of the fibre, resulting in phase and polarisation modulation of the individual modes supported
35 in the fibre. [Spillman et. al., "Statistical-Mode Sensor f r Fiber Optic Vibration Sensing Uses", *Applied Optics*, Vol. 28, pp. 3166-3176, 1989] Each mod is modulated

- 3 -

5 differently and therefore travels a different path to the
end-face of the fibre. The transmitted modes in the fibre
combine or interfere at the fibre end-face and the pattern
is received by the detector. The observed interference
pattern is in the form of a chaotically distributed speckle
10 pattern. Any external perturbations acting on the fibre
randomly redistributes the speckle pattern with a resultant
amplitude modulation perceived at the detector. Because
this arrangement is very sensitive to external variations
15 and the amplitude modulation is generally nonlinearly
related to the phase and polarisation modulation, the
resultant output signal suffers deep fading and drifting.
[Rawson et. al., "Experimental and Analytical Study of
Modal Noise in Optical Fibers", *Proceedings: Sixth European*
20 *Conference on Optical Communication*, pp. 72-75, 16-19
September, 1980] This behaviour limits the use of
multimode fibres in systems which require signal stability
and reliability.

20 Researchers have analysed the spatial-temporal
coherence function propagation in multimode fibres when
propagated by a coherent source of radiation. [De Marchis
et. al., "Modal Noise in Optical Fibres", *Proceedings:*
Sixth European Conference on Optical Communication, pp. 76-
79, 16-19 September, 1980] [Spillman et. al., "Statistical-
25 Mode Sensor for Fiber Optic Vibration Sensing Uses",
Applied Optics, Vol. 28, pp. 3166-3176, 1989] [Ignatyev et.
al., "Fiber Optic Interferometric Sensors Using Multimode
Fibers", *SPIE Proceedings: Fiber Optic and Laser Sensors*
IX, Vol. 1584, pp. 336-345, 1991] They found that the
30 spatial-temporal coherence function at the multimode fibre
end-face is represented as a sum of stationary and non-
stationary terms related to the spatial and temporal
coherence properties of the optical signal and waveguide.
Summarising their calculations, they derived that a
35 multimode fibre with a given index profile possesses
spatial coherence filtering properties, even for a
spatially incoherent source of input radiation. In

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particular, Ignatyev et. al. predicted that the spatial coherence of the radiation that has passed through quite long lengths of multimode fibre (over 2 meters) is spatially stationary and has a coherence radius related to the wavelength (typically 2 to 3 μm at $\lambda=633\text{ nm}$) and fibre numerical aperture. Therefore, the central core region of the multimode fibre end-face with a radius less than or equal to the coherence radius could be considered spatially coherent and stationary. Therefore, if the inner core region of the multimode fibre could be monitored independently from the entire core cross-section, it should yield improved linearity in the amplitude modulation resulting in a reduction in signal fading and drifting.

A number of methods for isolating either individual modes or the inner core region of a multimode fibre have been disclosed in the art. One such method involves placing a singlemode fibre in close proximity to various locations on the end-face of a multimode fibre in order to selectively excite a single or limited number of modes in the multimode fibre and thus stabilise the fibre output. [White and Cooper, "Selective Excitation of the Modes of Multimode Graded Index Fibers", *Proceedings: Sixth European Conference on Optical Communications*, pp. 95-98, 16-19 September, 1980]

In a second method, and the most common known in the art, an external lens and spatial filter arrangement is used to isolate regions of the speckle pattern output of a multimode fibre such that a photodetector can measure the optical power in a given group of modes. Vibration or acoustic emission sensing based on this principle has been successfully demonstrated in numerous application areas. [Fuhr et. al., "Simultaneous Single Fiber Optical Communications and Sensing for Intelligent Structures", *Smart Materials and Structures*, Vol. 1, pp. 128-133, 1992]

[Cosgrave et. al., "Acoustic Monitoring or Partial Discharges in Gas Insulated Substations Using Optical Sensors", *IEE Proceedings-A*, 140(5) pp.369-374, 1993] [El-

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Sherif and Ko, "Smart Textile Composites by Co-Braiding of Fiber Optic Sensors", *Proceedings: Ninth International Conference on Composite Materials (ICCM-9)*, Madrid, Spain, Vol. 2, pp.402-404, July, 1993]

5 These prior art methods, however, suffer from a number of disadvantages. Mechanical support is generally needed to align and maintain alignment of the fibre, lens and external spatial filter, therefore increasing the overall bulk and expense of the final system. In addition,
10 the arrangement would be susceptible to noise and inconsistencies resulting from environmental conditions, ie. temperature fluctuations, vibrations and fouling of optical surfaces. Furthermore, for practical applications, the sensing region of the fibre cannot be localised and,
15 therefore, the system would suffer from lead-in fibre sensitivity.

 Another significant disadvantage of the prior art methods utilising external spatial filters is that the optical signal is coupled out of the fibre in only a
20 forward or lateral direction, but not in the reverse direction, as is often required in preferred applications.

 In a third prior art method, Ignatyev et. al. predicted that a narrow core fibre, if coupled directly to the "coherence" radius region of a larger-core fibre, would
25 perform the function of an optical spatial coherence filter or diaphragm and hence greatly improve the quality of the transmitted beam, ie. improved linearity, reduced signal fading, reduced signal drift, etc. [Ignatyev et. al., "Fiber Optic Interferometric Sensors Using Multimode
30 Fibers", *SPIE Proceedings: Fiber Optic and Laser Sensors IX*, Vol. 1584, pp. 336-345, 1991] However, their suggested embodiments of the sensors still required the optical signal to be coupled out of the fibre in only a forward or lateral direction, but not in the reverse direction, as is
35 often required in preferred applications.

 Soon afterwards, Tapan s and Rossit r sel ct d and monitored a small diameter, central regi n of a

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multimod fibre end-face by placing a singlemode fibre diaphragm in close proximity to the multimode fibre and found that the concept was sound. The response of the multimode fibre, which was previously chaotic, had become

5 stable and displayed a good quantitative response. Furthermore, by extending the singlemode fibre to a sufficient length the signal to noise ratio (SNR) was found to be greatly improved. [Tapanes and Rossiter, "Practical Application of Fibre Optic Sensors to Engineered

10 Structures", *Proceedings: Australian Conference on Optical Fibre Technology-17 (ACOFT-17)*, Hobart, Tasmania, Australia, pp. 210-213, Nov/Dec, 1992] [Tapanes and Rossiter, "Practical Application of Fibre Optic Sensors to Engineered Structures for Real-Time, Nondestructive

15 Evaluation Using a Composite Material Patch", *Proceedings: Ninth International Conference on Composite Materials (ICCM-9)*, Madrid, Spain, Vol. 2, pp. 405-412, July, 1993]

Tapanes and Rossiter constructed a multimode sensor using a singlemode pigtailed laser diode operating

20 at $\lambda=670.6$ nm. The laser diode pigtail was FC-connected to one port of a 633 nm singlemode, 3 dB (2X2) fibre optic coupler. A 1300 nm singlemode fibre with 9/125 μm core/cladding diameter and mirrored end-face was mechanically coupled to one of the sensor ports of the

25 (2X2) coupler using a Dorran mechanical splice. The other unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was ST-connected to a photodiode. The 1300 nm singlemode fibre was used as the multimode (approximately 4 modes) sensing

30 fibre and the 633 nm, 3.7 μm core diameter fibre-lead of the coupler was used as a diaphragm as well as to deliver and return the optical signals to/from the sensing region. The sensor lengths used were typically 70 mm in length.

Tapanes and Rossiter overcame some of the

35 disadvantages of prior art techniques by using a mechanical splic to maintain alignment of the single and multi moded fibr s by butting the fibr s against one another and

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mechanically locking them in that position. The precision V-groove of the mechanical splice and the identical overall diameters of the two fibres ensured that the core of the singlemode fibre was maintained in alignment with the central region of the multimode fibre end-face. Furthermore, by mirroring the end-face of the multimode fibre, the optical signal returned to the optical system components in the reverse direction, as is often required in practical applications. This arrangement resulted in a so called "multimode fibre optic interferometer" with very good response linearity, as well as reduced drift and signal fading.

This prior art method, however, suffers from a number of disadvantages. The mechanical splice requires mechanical support to prevent environmental conditions from affecting the fibres' alignment and separation within the splice cavity. This disadvantage requires that the mechanical splice be located well away from the sensing region and that the multimode fibre sensor be of sufficient length to allow for this. Therefore, the localisation of the sensor in this prior art technique is limited to relatively long lengths (usually 50 mm and greater). Furthermore, mechanical splices are manufactured to couple fibres of standard diameters (125 μm). This limits the choice of optical fibre to standard telecommunication types, which may not necessarily be the most appropriate for a specific sensing application. In addition, mechanical splices do not couple fibres of different diameters and therefore, once again, limits the possible combination of fibres used.

The present invention provides a method for producing a sensor, including:

providing a singlemode optical fibre formed from a waveguide material and having a fibre core;

providing a multimode waveguide and having a waveguide core;

fusing splicing the singlemode fibre and

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multimode waveguide so that centres of the cores of the singlemode fibre and multimode waveguide are aligned and remain fixed at the splice; and

5 cleaving or polishing the multimode waveguide, after the fusion splicing, at a desired location spaced from the splice to localise the sensor.

10 In the sensor according to the invention a singlemode of electromagnetic radiation is launched into the singlemode fibre from a light source such as a laser and propagates along the singlemode fibre. When the light source reaches the multimode waveguide the singlemode can branch out into multiplemodes within the multimode waveguide so that when the multimode fibre experiences a change due to the change in the environment it is

15 monitoring, properties of the electromagnetic radiation in the multimode waveguide can be altered. Light which has had its property altered in the multimode waveguide enters the singlemode fibre from the multimode waveguide for detection by the detecting device. Cleaving or polishing

20 of the multimode waveguide for application of a mirroring material to reflect radiation back to a detector or fusion splicing of a singlemode fibre for enabling light to pass from the multimode waveguide to the singlemode fibre and then to a detector without reflection enables size of the

25 sensing portion, namely the multimode waveguide, to be controlled so that the sensing portion can be made considerably smaller than in prior art devices.

30 Preferably the singlemode and multimode fibres are prepared prior to fusion splicing by cleaving or polishing ends of the singlefibre and multimode waveguide to establish flat smooth surfaces at the ends of the singlemode fibre and multimode waveguide which are to be fusion spliced.

35 Preferably the cleaving or polishing at the desired location spaced from the fusion splice establishes a flat smooth surface at the desired location.

Preferably the flat smooth surfac at the desired

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1 cati n is coat d with a mirroring mat rial to refl ct
radiation back through the multimode waveguide and then the
singlemode fibre to a detecting device. However, in
another embodiment the cleaved or polished multimode
5 waveguide is fusion spliced at a desired location to a
singlemode fibre which in turn is coupled to a detecting
device.

Preferably the singlemode fibre is coupled to a
light source, and a detecting device.

10 Preferably a plurality of multimode waveguides
and singlemode fibres are fusion spliced in end-to-end
relationship to form a quasi-distributed sensor.

In other embodiments a plurality of singlemode
fibres are fusion spliced to respective multimode
15 waveguides and the plurality of singlemode fibres are
connected to a coupler which in turn is connected to a
further singlemode fibre to form a multiplexed sensor.

Preferably the multimode waveguide is a multimode
fibre.

20 Thus preferably the invention may be said to
reside in a method for producing a waveguide sensor,
including, but not limited to, the steps of:

Preparing a singlemode and a multimode fibre by
cleaving or polishing their ends so as to establish a flat,
25 smooth surface. After taking necessary precautions to
remove any contaminants from the cleaved or polished fibre
end-faces, the fibres are placed end-to-end in a fusion
splicing apparatus and fused together using the appropriate
or desired fusion arch times and currents. The fusion
30 splicing procedure may be repeated a number of times if
necessary. Although it is not imperative, a preferred
procedure for splicing the fibres involves setting the
fusion splicing parameters such that the fibres are
abruptly fused and not wholly fused in a tapered-like
35 manner, such that a visible line separating the fibres is
observable. In this manner, the smaller cor of the
singlemode fibr does not taper or merg with th larger

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core of the multimode fibre and, therefor, essentially retains the original diaphragm size. The core and overall diameters of the fibres is not limited and translation stages and/or V-grooves may be used on the fusion splicing apparatus to centrally align the cores of the two fibres before the fusion splicing procedure. Different combinations of single and multi mode fibres may require a different or unique set of fusion splicing parameters.

Preparing or connectorising the free end of the singlemode fibre in any manner which facilitates attaching, connecting or coupling the singlemode-fibre-part of the sensor to the appropriate combination and arrangement of light source, coupler, photodiode and signal processing electronics.

Cleaving or polishing the multimode fibre at any location after the fusion splice so as to establish a flat, smooth surface. The position of the cleave or polished surface establishes the localised length or sensing region of the sensor. Therefore, it is possible to produce localised sensing lengths less than 1 mm long. There is no limit to the maximum length, other than those imposed by the optical attenuation and scattering of the waveguide material, by induced microbend losses or by limitations of the optical components in the system. After taking necessary precautions to remove any contaminants from the cleaved or polished multimode fibre end-face, a selected portion of the fibre, including the end-face of the multimode fibre, is mirrored with a suitable mirroring material (ie.. a metal or dielectric material).

A preferred method for mirroring the multimode fibre end-face involves placing the fibre in a vacuum system and the prepared fibre end-face is then coated with a metallic material such as Au, Ag, Al or Ti or a dielectric material such as TiO_2 . This coating can be prepared by using thermal evaporation, electron beam evaporation or sputtering. Other coating or mirroring materials and techniques may also be utilised.

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In an optional embodiment, the manufactured sensor and/or the exposed fusion spliced region may be protected by encapsulating or coating the desired region in a suitable material (ie. ultraviolet acrylate, epoxy, etc.).

Any suitable light source, coupler and photodetector may be used with the sensor. The required optical properties of the light source are such that light may be launched into and propagated in the singlemode waveguide. For localisation, the light propagated in a singlemode fibre should remain singlemode during the entire period of travel in the singlemode fibre. Once the light is launched into the multimode fibre from the singlemode fibre, several modes may be excited and the multimode fibre will be sensitive to various parameters. Once the light is launched back into the singlemode fibre from the multimode fibre, only a single mode is supported and travels to the optical components of the system. Lead-in/lead-out fibre desensitisation and sensor localisation is achieved in this manner. In practical applications, the singlemode fibre should be made sufficiently long to attenuate all cladding modes in order to improve the signal-to noise ratio.

The invention also provides a sensor including:
a singlemode optical fibre formed from a waveguide material and having a fibre core; and
a multimode waveguide and having a waveguide core, the multimode waveguide being fusion spliced to the singlemode optical fibre so that centres of the cores of the singlemode waveguide and multimode fibre are aligned and remain fixed at the splice; and

wherein the multimode waveguide is cleaved or polished, after fusion splicing, at a desired location spaced from the fusion splice to localise the sensor.
Preferably the cleaving or polishing at the desired location spaced from the fusion splice establishes a flat smooth surface at the desired location.

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Preferably the flat smooth surface at the desired location is coated with a mirror material to localise the sensor.

In another embodiment the cleaved or polished multimode waveguide is fusion spliced to a further singlemode fibre which is coupled to a detecting device.

Preferably the sensor includes a light source and a detecting device.

In the preferred embodiment of the invention the light source and detecting device are coupled to the singlemode fibre so that radiation, in use, is launched into the singlemode fibre and propagates along the singlemode fibre and also along the multimode waveguide wherein properties of the radiation are altered due to changes in a parameter which is to be monitored, and the radiation is reflected from the mirroring material back along the multimode waveguide and singlemode fibre for detection by the detecting device.

In some embodiments of the invention a plurality of multimode waveguides and singlemode fibres are fusion spliced end-to-end to provide multi-distributed sensors. In other embodiments a plurality of singlemode fibres are fusion spliced to multimode waveguides and the singlemode fibres are coupled to a coupler which is in turn coupled to a further singlemode fibre to produce a multiplexed sensor.

The waveguide sensors according to this invention can be used in real-time to monitor engineering structures and fabricated items. Their small size enables them to be used in difficult-to-reach areas or embedded non intrusively in an object for in-situ monitoring. The concept of incorporating the waveguide sensors into a patch body provides protection for the sensor and allows the patch body to be adhered to the surface of existing or completed structures.

Utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor also enables monitoring to take place in a

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non-destructive manner. Thus, the sensor is not necessarily fractured or destroyed in order to monitor the desired parameter.

5 The effective sensing length of the waveguide sensor can be varied for either point or integrated sensitivity. Multi-point sensing can be achieved by quasi-distributed, distributed or multiplexed configurations.

10 Preferably the waveguide comprises at least one optical fibre and/or at least one optical fibre device. In some embodiments of the invention the waveguide may merely comprise an optical fibre without any additional sensing elements. However, the optical fibre can include sensing elements at its end or along its length and those sensing
15 elements can comprise devices which will respond to a change in the desired parameter in the environment of application and influence the properties and characteristics of the electromagnetic radiation propagating in the waveguide to thereby provide an
20 indication of the change in the parameter.

The waveguide or waveguides may be formed from any glass material, hard oxides, halides, crystals, sol-gel glass, polymeric material or may be any form of monolithic substrate.

25 Electro-optic devices, acousto-optic devices, magneto-optic devices and/or integrated optical devices may also be utilised in the sensing system.

Preferably the fusion splicing takes place in a fusion splicer or by laser welding techniques, or by any
30 other technique to fuse the multimode waveguide and singlemode fibre.

Preferred embodiments of the present invention will be further illustrated, by way of example, with reference to the following drawings in which:

35 Figure 1 is a view showing an embodiment of the invention illustrating fusion splicing and mirroring;

Figure 2 is a more detailed view of the

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embodiment of figure 1;

Figure 3 is a view showing a further embodiment of the invention;

Figure 4 is a view showing a still further embodiment of the invention; and

Figure 5 is a view showing yet a further embodiment of the invention.

With reference to figure 1, a singlemode fibre 14 and a multimode fibre 18 are prepared by cleaning their ends so as to establish a flat, smooth surface. After taking necessary precautions to remove any contaminants from the cleaved fibre end-faces, the fibres are placed end-to-end in a fusion splicing apparatus and fused together at 17 using the appropriate or desired fusion arch times and currents. The multimode fibre 18 is then cleaved at any location after the fusion splice 17 so as to establish a flat, smooth surface. The position of the cleave or polished surface establishes the localised length or sensing region of the sensor 12. After taking necessary precautions to remove any contaminants from the cleaved multimode fibre end-face, a selected portion 15 of the fibre, including the end-face of the multimode fibre, is mirrored with a suitable mirroring material (ie., a metal or dielectric material).

In the embodiment of figure 2, a fibre optic modalmetric sensor 10 according to the preferred embodiment comprises a multimode fibre 18 which is mirrored on its end-face 15 and fusion spliced 17 to a singlemode fibre patch cord 16. The free end of the fibre optic modalmetric sensor 10 can be adhered to an engineering structure or manufactured article. The singlemode fibre patch cord 16 is coupled to instrumentation 20 which includes a light source 22, coupler 26 and a detector and signal processing unit 24. The patch cord 16 can be of any desired length, and indeed up to several kilometres, so the instrumentation 20 can be located remote from the multimode fibre 18 which forms the sensing element of the sensor 10. The light

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source 22 provides light which is propagated along the singlemode fibre 14 in the singlemode fibre patch cord 16 and, which in the embodiment of figure 2, is reflected back along the optical fibre for detection by the unit 24.

5 However, in other embodiments the detecting unit 24 could be located at the end of the optical fibre and the transmitted wave could merely be detected by the unit 24 without the need for reflection. The propagated light in the multimode fibre 18 which is eventually detected by the
10 detector unit 24 has its properties and characteristics altered by a change in a desired parameter which is to be monitored.

 In this embodiment and the other embodiments to be described in the following description, the multimode
15 fibre 18 and a small part of the singlemode fibre 14/patch cord 16 is located on a patch body (not shown) of host material to enable the sensor to be conveniently attached to a structure or the like.

 In the embodiment of figure 3, a singlemode
20 optical fibre patch cord 16 is coupled to the light source 22. A multimode fibre 18 is then fusion spliced to the singlemode fibre 16 in the same manner as described with reference to figures 1 and 2. The other end of the multimode fibre 18 is cleaved and prepared in the manner
25 referred to above and fusion spliced to a further singlemode fibre 14. The singlemode fibre 14 is fusion spliced to a multimode fibre 18 which is in turn is fusion spliced to a singlemode optical fibre patch cord 16 which is coupled to the detector and signal processing device 24.
30 In this embodiment of the invention a quasi-distributed sensor is produced which has sensing portions formed by the two multimode fibres 18 wherein the propagated electromagnetic radiation is received by the detector 24 at the end of the optical path rather than by reflecting the
35 radiation back from a mirrored end 15 as in the embodiment of figure 2.

 In the embodiment of figure 2, the patch cord 16

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including the singlemode fibre, connected to detector 24, could be replaced with a multimode fibre. Depending on the length of the multimode fibre, results may not be as good as the arrangement shown in figure 2 because of drift or interference in the multimode fibre which replaces the patch cord 16.

In the embodiment of figure 4, a quasi-distributed sensor arrangement 30 is illustrated. This arrangement is made possible by fusion splicing 17 insensitive singlemode fibre 14 sections between the sensitive multimode fibre 18 sections.

In the embodiment of figure 5, a multiplexed fibre optic modalmetric sensor system 40 is illustrated. A (1XN) star coupler 42 joins the singlemode optical fibre patch cords 16 to one individual singlemode optical fibre patch cord 44. This type of configuration would be capable of mapping parameter fields.

The primary applications of the fibre optic modalmetric sensor according to the preferred embodiments of this invention is in structural integrity monitoring and machine condition monitoring. The sensor could be used to monitor a wide variety of structures and machinery, for example: metal or composite material aerospace structures, satellites, marine vessels, submersible vessels, storage vessels, off-shore structures, pipelines, chemical storage containers, power transformers, power generators, hydro electric dams, gearboxes, motors, compressors, buildings, bridges, etc. Other parameters could also be monitored depending on the type of waveguide or sensor arrangement employed.

The sensors are capable of monitoring parameters in a reliable and non destructive manner. In other words, the sensor waveguide does not rely on failure, fracture, breakage or any other form of permanent, irreversible change.

Preferred embodiments of the invention have been tested illustrated by the following examples. The sensors

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were constructed in order to determine the feasibility of producing localised fibre optic modalmetric sensors with relatively short sensing lengths. Parameters monitored with the fibre optic modalmetric sensors included strain, vibration, structural resonance, frequency analysis, acoustic emission, sound, temperature and proximity. Not all of the results obtained to date are detailed in the following examples.

Example 1:

10 A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at $\lambda=670$ nm. The laser diode pigtail was fusion spliced to a 633 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 3.5/125 μm core/cladding diameter to an optical fibre with 9/125 μm core/cladding diameter. The multimode (larger core) fibre was cleaved approximately 10 mm from the fusion splice location and mirrored. The singlemode fibre free-end was fusion spliced to one of the sensor ports of the (2X2) coupler. The unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was ST-connected to a ST-receptacled silicon photodiode. The sensor was then adhered to a steel cantilever beam with Ciba Geigy Araldite 24 hour epoxy. An electrical strain gauge (ESG) was also adhered to the beam using a cyanoacrylate adhesive, co-located with the fibre optic sensor, in order to compare results. The steel beam was placed in a cantilever load frame and deflected. Dynamic experiments were performed by deflecting the beam tip and releasing. The sensor signal output (vibration) and frequency response (via a Fast Fourier Transform) were compared with the ESG response. In each case the sensor response showed excellent correlation with the ESG response. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor.

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Example 2:

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at $\lambda=1300$ nm. The laser diode pigtail was fusion spliced to a 1300 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 9/125 μm core/cladding diameter to an optical fibre with 50/125 μm core/cladding diameter. The multimode (larger core) fibre was cleaved approximately 10 mm from the fusion splice location and mirrored. The singlemode fibre free-end was fusion spliced to one of the sensor ports of the (2X2) coupler. The unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was fusion spliced to a fibre pigtailed InGaAs photodiode. The sensor was then adhered to a steel cantilever beam with Ciba Geigy Araldite 24 hour epoxy. An electrical strain gauge (ESG) was also adhered to the beam using a cyanoacrylate adhesive, co-located with the fibre optic sensor, in order to compare results. The steel beam was placed in a cantilever load frame and deflected. Dynamic experiments were performed by deflecting the beam tip and releasing. The sensor signal output (vibration) and frequency response (via a Fast Fourier Transform) were compared with the ESG response.

In each case the sensor response showed excellent correlation with the ESG response. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor

Example 3:

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at $\lambda=1300$ nm. The laser diode pigtail was fusion spliced to a 1300 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 9/125 μm core/cladding diameter to an optical fibre with 100/140 μm core/cladding diameter. The multimode

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(larger core) fibre was cleaved approximately 10 mm from the fusion splice location and mirrored. The singlemode fibre free-end was fusion spliced to one of the sensor ports of the (2X2) coupler. The unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was fusion spliced to a fibre pigtailed InGaAs photodiode. The sensor was then adhered to a steel cantilever beam with Ciba Geigy Araldite 24 hour epoxy. An electrical strain gauge (ESG) was also adhered to the beam using a cyanoacrylate adhesive, co-located with the fibre optic sensor, in order to compare results. The steel beam was placed in a cantilever load frame and deflected. Dynamic experiments were performed by deflecting the beam tip and releasing. The sensor signal output (vibration) and frequency response (via a Fast Fourier Transform) were compared with the ESG response. In each case the sensor response showed excellent correlation with the ESG response. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor.

Example 4:

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at $\lambda=1300$ nm. The laser diode pigtail was fusion spliced to a 1300 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 9/125 μm core/cladding diameter to an optical fibre with 100/140 μm core/cladding diameter. The multimode (larger core) fibre was cleaved approximately 300 mm from the fusion splice location and mirrored. The singlemode fibre free-end was FC-connectorised and connected to a FC receptacled sensor port of the (2X2) coupler. The unused sensor port arm was fractured to minimise end reflections. The remaining output port of the coupler was fusion spliced to a fibre pigtailed InGaAs photodiode. The sensor was then encapsulated in a thin layer of Ciba Geigy Araldite 24

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hour epoxy and embedded in a concrete beam. The concrete beam was placed in a three-point bend apparatus and deflected. The response of the sensor showed excellent agreement with the magnitude and frequency of the applied force. The concrete beam was also impacted with a steel hammer and the sensor response showed the expected, high frequency response characteristics. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor.

Optical devices made by the method of the invention and optical devices according to the invention are useful in a wide variety of applications and fields. Not inclusive, but indicatively, the following examples illustrate some applications in which the fibre optic modalmetric sensor may be used:

- Aerospace structures operate on extremely tight tolerances and safety criteria. As a consequence, aerospace structures are often inspected at frequent intervals using labour intensive non-destructive techniques. Electrical strain gauges and piezo-electrics cannot be incorporated into the structure without detrimental effects and have a limited fatigue life. As a consequence, real-time structural integrity monitoring is rarely achieved in aerospace structures, except perhaps in sophisticated military research projects. The fibre optic modalmetric sensor, alternatively, can be adhered to the inner-surface of aerospace structures, thus not affecting the aerodynamics, and yet provide the following advantages over conventional sensors: they can perform quasi-static or dynamic measurements, have very high fatigue life, are corrosion resistant, are non-conductive, are capable of point or distributed sensing, can be configured to any shape or contour, and a single sensor is capable of monitoring several parameters simultaneously. Furthermore, it is

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possible to embed the optical sensor in composite components to perform in-situ monitoring.

- Off-shore oil-rigs are generally routinely inspected by divers or robots for structural integrity. The harsh, corrosive environment renders it nearly impractical to attach conventional sensors to the structure. As a result, cracks or any other form of damage cannot be detected in its early stages and could possibly grow to within catastrophic levels before it is visually found. Electrical strain gauges would require long wire lead lengths to reach the desired sensing region, thus electrical noise would be a large limitation. Piezo-electric sensors have a major limitation in that they are a dynamic material, whereas vibrations in oil-rigs are generally quasi-static (< 2 Hz). In addition, electrical devices are prone to corrosion damage which would limit their lifetime substantially. Fibre optic modalmetric sensors are not only resistant to corrosion, but they could possibly monitor the extent of corrosion of the structure. Lightning strikes would severely effect electrical or conductive devices, whereas optical sensors are generally not affected by this type of strike. The fibre optic modalmetric sensors can be reliably adhered to critical areas of off-shore oil-rigs (ie. underwater support structures) and thus offers the opportunity to monitor the structural integrity in real-time. On-board the oil-rig, fibre optic modalmetric sensors could continuously monitor structural vibrations.
- Naval vessels (ships or submersibles) are generally monitored by divers or in dry docks for structural integrity. The limitations of conventional sensors in this case are the same as those discussed for off-shore oil rigs. Fibre optic modalmetric sensors would be extremely useful for these structures as the world-wide fleet is generally quite old and ageing

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rapidly. A particular advantage of a fibre optic modalmetric sensors for use in these structures is the ability to monitor relatively large areas and to localise the sensing regions. Conventional sensors are usually limited in size. The longer/larger sensor types that do exist are usually very expensive. The fibre optic modalmetric sensors, on the other hand, can be configured to any desired length/size with only a marginal increase in cost and complexity.

Power stations and transformers are critical structures to monitor as they tend to over-heat and have vibrational problems which could result in extremely dangerous explosions. Conventional sensing techniques suffer extreme electrical noise problems when monitoring these structures due to electro-magnetic interference (EMI). Fibre optic modalmetric sensors can easily be adhered to these structures to monitor temperature, vibrations, cracking, strains and stresses, and several other important parameters in real-time, without the noise limitations.

Insulation degradation of large power equipment is one of the major concerns of electricity supply authorities. Forced outage of a large generator or transformer due to insulation breakdown can cost millions of dollars in repair and outage costs. The potential for generator and transformer outage is ever increasing as a large proportion of the capital equipment in the Australian and international electrical industry is nearing its expected lifetime. Replacement and refurbishment of these major components has significantly slowed down because of economic restraints and many are now operating beyond their expected operational lifetime. Therefore, it is important to closely monitor the insulation condition of these components and determine the remnant life of the electrical generating plant.

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Partial discharge (PD) measurements have been one of the most effective diagnostic tools for monitoring the insulation condition of high voltage equipment.

5 In-service measurements of partial discharges in generators and transformers are extremely difficult because of large interference effects from various sources, particularly EMI. Investigations have been carried out in the world to develop reliable detection techniques and devices, however, no successful
10 breakthrough has until now been achieved. The fibre optic modalmetric sensor offers a new technique for PD measurements in the power industry by monitoring minute, high frequency acoustic emission signals in the structure. Machine condition monitoring can be
15 performed simultaneously with the fibre optic modalmetric sensor by low-pass filtering the signal and performing frequency analysis of the structural resonances. The fibre optic modalmetric sensor offers several advantages over other PD detectors currently
20 under development around the world, these include: less complex, small size, ease of use, safer for the high voltage equipment insulation, more reliable for noise discrimination (immunity to EMI) and cost effective.

25 - Undersea pipelines are generally not monitored at all due to the lack of any reliable and durable sensing techniques. If something goes wrong with a pipeline (ie., cracking, corrosion, etc.) it is usually realised when the output flow is affected. No
30 information is available as to the type and location of the fault. Obviously, this is an inefficient and potentially costly situation. Not only has the flow of goods stopped, but the pipeline has to be pulled up or divers/robots need to go down to have a look for
35 the fault. Undersea pipelines are in a very harsh and corrosive environment. In addition, their lengths can vary from a few meters to several hundred kilometres

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- in length. Conventional conductive sensors would have difficulties surviving the environment and because of the long lengths of wire-leads required they would suffer from electrical noise problems. Undersea optical fibre communication cables have proved their capabilities in long-haul (> 1000 km) applications, therefore optical fibre sensors could be useful in long-haul sensing requirements.
- The chemical and petrochemical industries have an ongoing need to monitor the structural health and integrity of all their reaction and containment tanks/vessels and cylinders. This can be achieved with semi-permanent, conventional techniques but durability and accuracy are essential or false alarms may result. The inherent advantages of the fibre optical modalmetric sensor makes it ideal for this application.
- The measurement of loads currently relies heavily on load cells which are configuration of resistive strain devices. The cells have a characteristic narrow load range within which accuracy and sensitivities are within tolerance. The narrowness of this operating range derives from the non-linearity of the electrical resistance response to strain, a feature which the fibre optic modalmetric sensor overcomes. Hence load cells constructed with fibre optic modalmetric sensor components should be more sensitive at most loads but cover a much broader range off loads. This would result in the current series of load cells being replaced by a single broad-range fibre optical modalmetric sensor cell. An added advantage would be the zero sensitivity of the fibre optic modalmetric sensor cells to electrical noise and harmonic responses to set frequencies of loading.
- Structural integrity monitoring applications in general.
- Machine condition monitoring applications in general.

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- Optical signal processing, conditioning, stabilisation and optimisation applications in general.

The fibre optic modalmetric sensor may be used in most applications where conventional sensors such as electrical strain gauges, accelerometers, thermocouples, make-break circuits and piezo-electric sensors are employed or might be employed if they were less limited. Not inclusive, but indicatively, the following examples illustrate some users of the fibre optic modalmetric sensor:

- Road, rail, dam and bridge construction and maintenance firms.
- Owners, operators and insurers of marine vessels.
- Petroleum and petrochemical companies.
- Power, water and fuel facilities.
- Tower owners and operators.
- Aircraft manufacturers and repairers.
- Airfleet operators.
- Automotive industry.
- Non-destructive evaluation firms and equipment manufacturers.
- R&D companies and laboratories.
- Wood pulp and paper manufacturers.
- Instrument and sensor manufacturers.
- Sports equipment and facilities manufacturers and operators.
- Off-shore oil rig operators and maintenance firms.
- Mine operators.
- Quality Assurance and safety firms.
- Building management firms.
- Industrial equipment operators and manufacturers.
- Security firms.
- Power plant manufacturers, owners or operators.
- Telecommunications firms or operators.
- Telecommunication components/devices manufacturers.

To date, the use of multimode fibre systems has been greatly limited by their undesired response

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characteristics. This significant disadvantage offsets the fibre's advantages of low cost and ease of fabrication. The fibre optic modalmetric sensor overcomes the inherent weaknesses, is easy to fabricate and costs relatively little to assemble.

Such a sensing system would offer low cost and increased safety advantages over existing technologies and has the potential for short to long term installation monitoring in plant, ecological (i.e., undersea) and other environments. Many applications of the fibre optic modalmetric sensor are possible because of its sensitivity, simplicity and cost effectiveness.

Since modifications within the spirit and scope of the invention may readily be effected by persons skilled within the art, it is to be understood that this invention is not limited to the particular embodiment described by way of example hereinabove.

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THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for producing a sensor, including:
providing a singlemode optical fibre formed from
a waveguide material and having a fibre core;
5 providing a multimode waveguide having a
waveguide core;
fusion splicing the singlemode fibre and
multimode waveguide so that centres of the cores of the
singlemode fibre and multimode waveguide are aligned and
10 remain fixed at the splice; and
cleaving or polishing the multimode waveguide,
after the fusion splicing, at a desired location spaced
from the splice to localise the sensor.
- 15 2. The method of claim 1 wherein the singlemode
fibre and multimode waveguide are prepared prior to fusion
splicing by cleaving or polishing ends of the singlemode
and multimode waveguide to establish flat smooth surfaces
at the ends of the singlemode fibre and multimode waveguide
which are to be fusion spliced.
- 20 3. The method of claim 1 wherein the cleaving or
polishing at the desired location spaced from the fusion
splice establishes a flat smooth surface at the desired
location.
- 25 4. The method of claim 3 wherein the flat smooth
surface at the desired location is coated with a mirroring
material to reflect radiation back through the multimode
waveguide and then the singlemode fibre to a detecting
device.
- 30 5. The method of claim 1 wherein the singlemode
fibre is coupled to a light source, and a detecting device.
6. The method of claim 1 wherein a plurality of

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multimode waveguides and singlemode fibres are fusion spliced in end-to-end relationship to form a quasi-distributed sensor.

7. The method of claim 1 wherein a plurality of
5 singlemode fibres are fusion spliced to respective multimode waveguides and the plurality of singlemode fibres are connected to a coupler which in turn is connected to a further singlemode fibre to form a multiplexed sensor.
8. The method of claim 1 wherein multimode
10 waveguide includes at least one optical sensing element.
9. The method of claim 1 including the step of coupling a light source and detector to the singlemode optical fibre.
10. The method of claim 1 including coupling a light
15 source to the singlemode fibre, fusion splicing a further singlemode fibre to the multimode waveguide at the desired location and coupling a detector to the further singlemode fibre.
11. The method of claim 1 wherein the multimode
20 waveguide is a multimode fibre.
12. A sensor including:
a singlemode optical fibre formed from a waveguide material and having a fibre core; and
a multimode waveguide having a waveguide core,
25 the multimode optical fibre being fusion spliced to the singlemode optical fibre so that centres of the cores of the singlemode fibre and multimode waveguide are aligned and remain fixed at the splice; and
wherein the multimode waveguide is cleaved or
30 polished, after fusion splicing, at a desired location spaced from the fusion splice to localise the sensor.

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13. The sensor of claim 12 wherein the cleaving or polishing at the desired location spaced from the fusion splice establishes a flat smooth surface at the desired location.
- 5 14. The sensor of claim 13 wherein the flat smooth surface at the desired location is coated with a mirror material to localise the sensor.
- 10 15. The sensor of claim 12 wherein the cleaved or polished multimode waveguide is fusion spliced to a further singlemode fibre which is coupled to a detecting device.
16. The sensor of claim 13 wherein the sensor is coupled to a light source and a detecting device.
- 15 17. The sensor of claim 16 wherein the light source and detecting device are coupled to the singlemode fibre so that radiation, in use, is launched into the singlemode fibre and propagates along the singlemode fibre and also along the multimode waveguide wherein properties of the radiation are altered due to changes in a parameter which is to be monitored, and the radiation is reflected from the mirroring material back along the multimode waveguide and
20 singlemode fibre for detection by the detecting device.
- 25 18. The sensor of claim 12 wherein a light source is coupled to the singlemode fibre for launching radiation into the singlemode fibre, and wherein a further singlemode fibre is fusion spliced to the desired location of the multimode waveguide and a detecting device is coupled to the further singlemode fibre for detecting radiation which is passed through the multimode fibre and which has had a property altered and wherein radiation propagates from the
30 multimode waveguide into the further singlemode fibre for detection by the detecting d vice.

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19. The sensor of claim 12 wherein the multimode waveguide is a multimode fibre.

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Fig 1

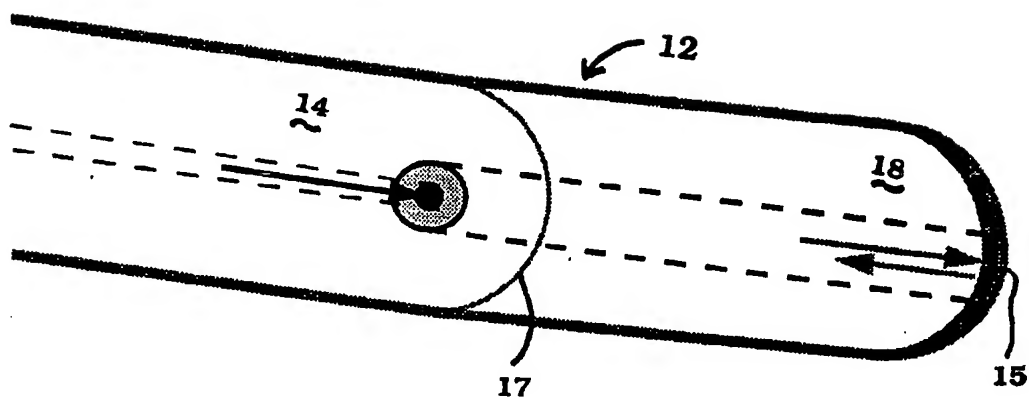
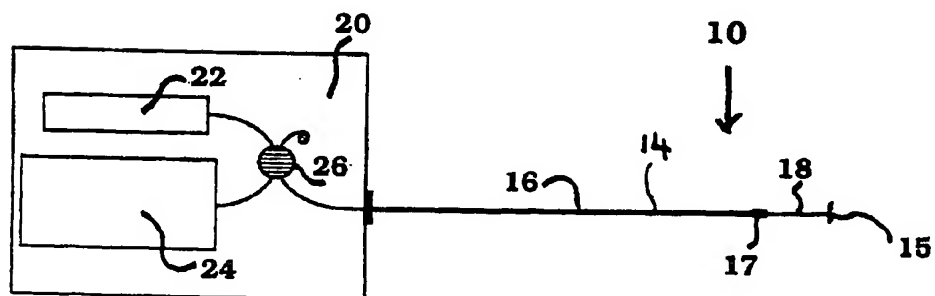


Fig 2



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Fig 3

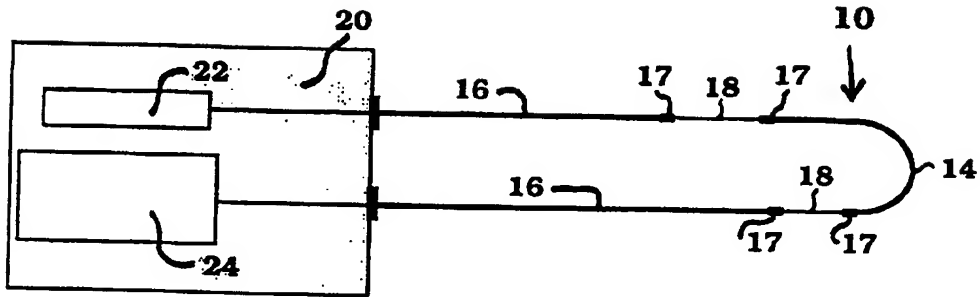


Fig 4

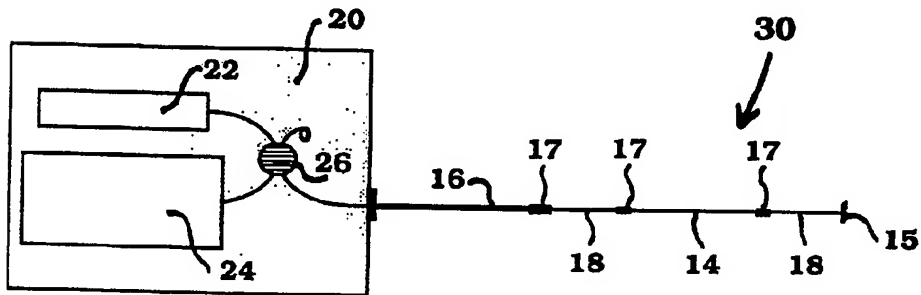
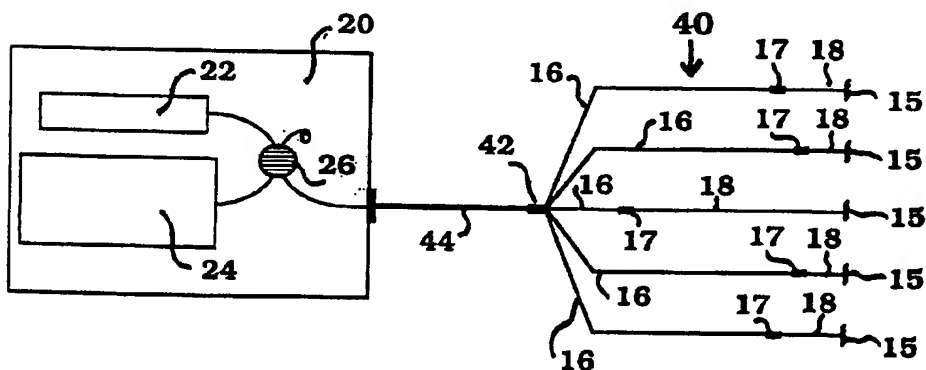


Fig 5



INTERNATIONAL SEARCH REPORT

International Application N.
PCT/AU 95/00568**A. CLASSIFICATION OF SUBJECT MATTER**Int Cl⁶: G01D 5/353, G01H 9/00, G01M 11/00, G01L 1/24, G02B 6/255.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHEDMinimum documentation searched (classification system followed by classification symbols)
IPC G01, G02Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as aboveElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DERWENT:

JAPIO: } (Single()Mode)and(Fiber# or Fibre#)and(Fusion()Splic:)

ENGINEERING INDEX:

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Patent Abstracts of Japan, P-1192, page 7, JP, 3-25381, A (Sumitomo Electric Ind. Ltd) 4 February 1991 abstract	1,8,11,12,19.
A	US, 5008545, A (ANDERSON ET AL) 16 April 1991 Whole document	
A	Patent Abstracts of Japan, P-1337, page 86, JP,4-5529, A (FUJIKURA LTD) 9 January 1992 abstract	



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
1 December 1995

Date of mailing of the international search report

11 DECEMBER 1995

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INTERNATIONAL SEARCH REPORT

International Application No.

PCT/AU 95/00568

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Patent Abstracts of Japan, P-1086, page 114, JP, 2-129611, A (NIPPON TELEGR & TELEPH CORP) 17 May 1990 abstract	
A	Patent Abstracts of Japan, P-569, page 153, JP, 61-270708, A (FURUKAWA ELECTRIC CO LTD) 1 December 1986 abstract	
A	Patent Abstracts of Japan, P-1039, page 124, JP 2-39110, A (NEC CORP) 8 February 1990 abstract	
A	Patent Abstracts of Japan, P-6, page 28, JP 55-17183, A (FUJITSU KK) 6 February 1980 abstract	

INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No.
PCT/AU 95/00568

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report				Patent Family Member			
US	5008545	JP	3-150442	DE	4033546	FR	2653621
END OF ANNEX							